Changes in freight cost and tariff

The transport cost for commodity k from country i to country j in any given year includes the cost of freight, import tariff (applied to the c.i.f. price), and export tariff:

(A.11) $c_{ijk} = f_{ijk} + t^{I}_{jk} (f_{ijk} + P_{ik,-1}) + t^{X}_{jk} P_{ik,-1}$

where c = transport cost, per unit of volume, f = freight cost, per unit of volume, t^I = import *ad valorem* tariff (Table B.5), P_{-1} = last year's equilibrium export price, and t^X = export *ad valorem* tariff.

Changes in trade inertia bounds

(A.12) $$T^L = T_{-1}(1 - \varepsilon)$$ $$T^U = T_{-1}(1 + \varepsilon)$$

ε = upper or lower bound on relative change in trade flow (Table B.5).

Appendix B

GFPM PARAMETERS FOR NEW ZEALAND

TABLE B.1–Elasticity of demand with respect to price and GDP

Product	Price	GDP
Fuelwood	–0.62	–1.50
Other industrial roundwood	–0.05	–0.58
Sawnwood	–0.16	0.32
Veneer and plywood	–0.13	1.20
Particleboard	–0.24	1.25
Fibreboard	–0.52	0.82
Newsprint	–0.05	0.21
Printing and writing paper	–0.15	0.80
Other paper and paperboard	–0.06	0.65

TABLE B.2–Elasticity of supply with respect to price, GDP per capita, and forest stock

Product	Price	GDP per capita	Forest stock
Fuelwood	2.00	0.00	1.50
Industrial roundwood	1.39	0.90	1.00
Other industrial roundwood	1.39	0.90	1.00
Other fibre pulp	0.80	1.00	
Waste paper	0.80	1.00	

TABLE B.3–Forest resource data and parameters

Parameter	Unit	Value
Forest stock	(10^6 m^3)	398
Forest stock growth rate	(% per year)	8.30
Forest area	(10^3 ha)	1827
Rate of forest area change	(% per year)	1.09
Fraction of fuelwood from forest		1.00

TABLE B.4–Manufacturing parameters

Input product	Manufactured product	Coefficient (m^3/m^3, m^3/t or t/t)	Change in coefficient (t/t)	Manufacturing cost* (US$/$m^3$ or US$/t)	Output elasticity of manufacturing cost
Industrial roundwood	Sawnwood	1.00		126.00	0.10
Industrial roundwood	Veneer and plywood	1.19		317.46	0.10
Industrial roundwood	Particleboard	0.80		116.20	0.10
Industrial roundwood	Fibreboard	0.72		214.48	0.10
Industrial roundwood	Mechanical pulp	1.07		209.28	0.10
Industrial roundwood	Chemical pulp	1.65		285.93	0.10
Mechanical pulp	Newsprint	0.58	0.000	177.56	3.00
Chemical pulp		0.30	–0.002		
Other fibre pulp		0.00	0.000		
Waste paper		0.12	0.002		
Mechanical pulp	Printing and writing paper	0.24	0.000	584.35	0.10
Chemical pulp		0.51	–0.001		
Other fibre pulp		0.00	0.000		
Waste paper		0.16	0.001		
Mechanical pulp	Other paper and paperboard	0.49	0.000	348.69	0.10
Chemical pulp		0.44	0.000		
Other fibre pulp		0.00	0.000		
Waste paper		0.08	0.000		

* Labour, capital, energy, and materials, exclusive of the cost of wood and fibre input.

TABLE B.5–Trade parameters*

Product	*Ad valorem* tariff (%)	Tariff reduction (% per yr)	Freight cost (US$/m^3 or US$/t)	Trade bounds (ε)
Industrial roundwood	0.0	0.0	12	0.030
Sawnwood	5.0	0.0	21	0.050
Veneer and plywood	2.0	0.0	16	0.052
Particleboard	5.0	0.0	7	0.069
Fibreboard	5.0	0.0	10	0.060
Chemical pulp	0.0	0.0	32	0.045
Printing and writing paper	7.0	–2.0	46	0.030
Other paper and paperboard	6.0	–1.0	40	0.051

* The trade bounds (or trade inertia) parameter, ε in Equation A.12 (Appendix A), is a bound on relative change in trade flow for a particular product, and is set at three times the standard error of the mean percentage change of world imports and exports of that product from 1970 to 1997 (Buongiorno *et al.* 2003).

Yield Trends Are Insufficient to Double Global Crop Production by 2050

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Abstract

Several studies have shown that global crop production needs to double by 2050 to meet the projected demands from rising population, diet shifts, and increasing biofuels consumption. Boosting crop yields to meet these rising demands, rather than clearing more land for agriculture has been highlighted as a preferred solution to meet this goal. However, we first need to understand how crop yields are changing globally, and whether we are on track to double production by 2050. Using ~2.5 million agricultural statistics, collected for ~13,500 political units across the world, we track four key global crops—maize, rice, wheat, and soybean—that currently produce nearly two-thirds of global agricultural calories. We find that yields in these top four crops are increasing at 1.6%, 1.0%, 0.9%, and 1.3% per year, non-compounding rates, respectively, which is less than the 2.4% per year rate required to double global production by 2050. At these rates global production in these crops would increase by ~67%, ~42%, ~38%, and ~55%, respectively, which is far below what is needed to meet projected demands in 2050. We present detailed maps to identify where rates must be increased to boost crop production and meet rising demands.

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Introduction

The world is experiencing rising demands for crop production, stemming from three key forces: increasing human population, meat and dairy consumption from growing affluence, and biofuel consumption [1–5]. By 2050, global agricultural production may need to be increased by 60%–110% to meet these increasing demands [3,6–7] as well as to provide food security to the ~870 million now chronically undernourished [8]. The only peer-reviewed estimate [3] suggests that crop demand may increase by 100%–110% between 2005 and 2050. Numerous authors have suggested that increasing crop yields, rather than clearing more land for food production, is the most sustainable path for food security [2,4,9–14]. Moreover, crop yield growth has been shown as an effective tool in reducing global poverty and undernourishment, as farmers themselves constitute the vast majority of the poor and the undernourished [15–17].

However, several recent studies indicate that yields may no longer be increasing in different regions of the globe [18–23]. Yields are no longer improving on 24–39% of our most important cropland areas [23]. Many of these areas are in top crop producing nations, having rising population, increasing affluence, or some combination of these factors [3,5,19,21–23]. This may increase difficulty of meeting future crop production goals but key unknowns remain for developing and targeting strategies: how are crop yields changing across the world, where gains in crop yields are able to meet growing demands, and where crop yields are falling behind.

Here we employ ~2.5 million statistics from a newly developed crop yield and area harvested database covering ~13,500 political units globally from 1961 to 2008, focusing on trends in the recent two decades [4,23]. We determine the rates of yield change in each political unit for the top four global crops: maize, rice, wheat, and soybean. These four crops together produce about two-thirds of current harvested global crop calories [3,18]. Using these data, we estimate the best-fit linear, non-compounding rates of yield change between 1989 and 2008 for these crops in each of these political units. Yield change is commonly modeled as a linear function of time [24–28] and such models have been used to project future crop yields [28–30]. We provide local, country, and global-scale rates of recent crop yield changes to determine where the rates of yield increase could double production by 2050, and where they are insufficient. The impact of negative or even slow rates of yield change in these crops could be severe, especially for low-income countries with rapidly rising population. The underlying data, period analyzed, statistical approach, and comparisons of yield projections are described in the Methods section below, with additional details and analysis in Text S1.

Results

The global average rates of yield increase across ~13,500 political units are 1.6%, 1.0%, 0.9%, and 1.3% per year for maize, rice, wheat, and soybean, respectively (Table 1, Figure 1). A ~2.4% per year rate of yield gains (non-compounding) is needed to double crop production by 2050. Current rates are thus not achieving this goal. At current rates only ~67%, ~42%, ~38%, and ~55% increases in maize, rice, wheat and soybean production, respectively, is possible by 2050.

We provide a range of future yield estimates by bootstrap sampling crop yield data at each of the political units studied for the period 1989 to 2008. The upper bound of the 90% confidence interval (Table 1, Figure 1) presents a slightly more optimistic scenario, global yields increase at rates of 2.4%, 1.4%, 1.8%, and 2.0% per year for maize, rice, wheat, and soybean, respectively. Yield trends following this upper bound projection could lead to ~101%, ~59%, ~76%, and ~84% increased production in these crops, respectively. The lower bound of our confidence interval provides us with a "worst-case scenario," wherein the global average yield of maize, rice, wheat, and soybean would increase at 0.8%, 0.5%, 0.1%, and 0.3% per year, respectively (Table 1, Figure 1). At these rates global production could only increase by ~34%, ~21%, ~4%, and ~13% for maize, rice, wheat, and soybean, respectively, by 2050. Further, the yield trajectory diverges, especially for rice and wheat from the 2.4% per year rate (Figure 1). See Figure S1 for spatial maps of r^2 at each political unit and statistical diagnostic tests (Text S1 and Figures S2, S3, S4, S5, S6, S7, S8, S9).

In the short term, due to population increases from ~6.7 billion in 2008 to ~8.0 billion in 2025 [5], the 1.6% and 1.3% per year global maize and soybean yield improvements may result in no significant change to the per capita global maize and soybean harvests. However, by 2050 there could be an increase. The much lower rates of rice and wheat yield increases, 1.0% and 0.9% per year, respectively, may result in no change to the per capita rice and wheat harvests to 2050. Thus, if we are to boost the production in these top four global crops that are now responsible for directly providing ~43% of the global dietary energy and ~40% of its daily protein supply [31] from yield increases alone, we have to immediately determine where and exactly by how much yields are changing. To further understand the yield trend patterns, we also track the rates of yield change within ~13,500 political units and report the results at the local and country scales.

Global trends mask the significant variations in the rates of yield change among and within countries (Figure 2). We determine where the within-country yield change rates are ~2.4% per year or above (i.e. doubling rates), where the rates are lower, and where yields are decreasing. We briefly describe these areas, emphasizing areas with doubling and decreasing rates as these areas define the places with the greatest opportunity to meeting growing demand or where to target investments. See Figure S10 for continuous rate (non-categorical) maps in kilograms/hectare/year/year. The influence of observed yields in 2008 on the percent rate of change is described in Figure S11 and related Text S1.

North and Central America

Most of North Dakota and Mississippi, northeastern South Dakota, northwestern Minnesota, and some isolated counties in other United States (U. S.) states are witnessing ~2.4% per year or greater rates of maize yield gains. Similar doubling rates in maize

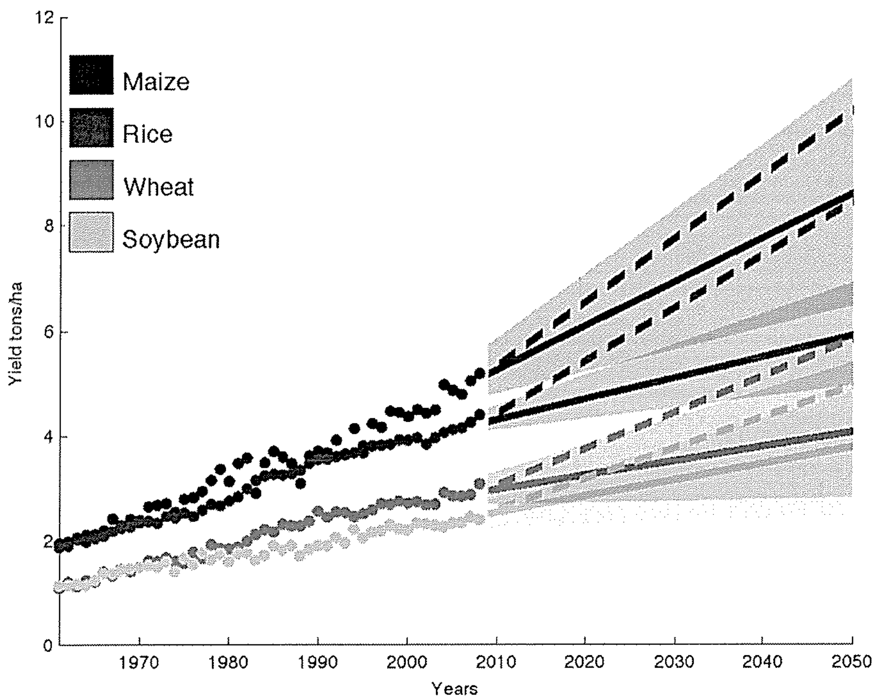

Figure 1. Global projections. Observed area-weighted global yield 1961–2008 shown using closed circles and projections to 2050 using solid lines for maize, rice, wheat, and soybean. Shading shows the 90% confidence region derived from 99 bootstrapped samples. The dashed line shows the trend of the ~2.4% yield improvement required each year to double production in these crops by 2050 without bringing additional land under cultivation starting in the base year of 2008.
doi:10.1371/journal.pone.0066428.g001

Table 1. Global summary for maize, rice, wheat, and soybean.

	MAIZE	RICE	WHEAT	SOYBEAN
Mean yield change per year (% per year)	1.6	1.0	0.9	1.3
Mean yield change per year (kg/ha/year/year)	84	40	27	31
Projected average yield in 2025 (tons/ha/year)	6.5	4.9	3.4	3.0
Projected average yield in 2050 (tons/ha/year)	8.6	5.9	4.1	3.8
Projected production in 2025 (million tons/year) at fixed crop harvested areas of 2008	1016	760	741	275
Projected production in 2050 (million tons/year) at fixed crop harvested areas of 2008	1343	915	891	347
Projected production shortfall in 2025, as compared to the rate that doubles production by 2050 (million tons/year)	100	160	157	43
Projected production shortfall in 2050, as compared to the rate that doubles production by 2050 (million tons/year)	247	394	388	107
Required extra land (million hectares) to produce the shortfall at 2025 projected yields	15	33	46	14
Required extra land (million hectares) to produce the shortfall at 2050 projected yields	29	67	95	28
Yield in the year 2008 (tons/ha/year)	5.2	4.4	3.1	2.4
90 percent confidence limit in yield change (%/year)	0.8–2.4	0.5–1.4	0.1–1.8	0.3–2.0
90 percent confidence limit in yield change (kg/ha/year/year)	41–124	21–58	4–52	6–50
90 percent confidence limit in production in 2025 (million tons/year) at fixed crop harvested areas of 2008	848–1203	687–846	599–898	214–328
90 percent confidence limit in production in 2050 (million tons/year) at fixed crop harvested areas of 2008	1009–1686	769–1072	618–1182	228–442

As an example consider yields and production in 2025 – the short term – and numbers by 2050 due to current rates of yield change. See Supplementary Data file for yield change rates per country.
doi:10.1371/journal.pone.0066428.t001

yields are found in the states of Chihuahua, coastal Sinaloa, most of Michoacán and Guanajuato and isolated areas of few other Mexican states as well as El Salvador. Maize yields are decreasing in parts of the U. S. Great Plains states (southern South Dakota, Kansas, Eastern Colorado and parts of southeastern Texas), eastern Mexico (San Luis Potosí, northern Durango, southeastern Coahuila, Nuevo León and Tamaulipas), and in Haiti and Guatemala (Figure 2a). The resultant impact is that the United States has the highest national rates of maize yield improvement in this region of the world (in kg/ha/year^2) followed by Canada, then Cuba, and Mexico (Data S1). In Central American countries such as Honduras and Nicaragua, where maize now provides ~27%, and ~25% of daily dietary energy, respectively [31], and in Panama (~7% of dietary energy), the production gains from their slower 0.5% per year yield improvement rates could be less than those required to keep pace with their population growth (in per capita harvested production terms). In Guatemala, where maize now provides ~36% of dietary energy [31] the yield trends are already negative (−0.7% per year), and as the population is projected to substantially increase [5], a steeper fall in the per capita harvested maize could occur.

Rice yield doubling rates are found only in some isolated areas of North and Central America. The United States has the highest overall rice yield improvement rates (1.2% per year), followed by Mexico (1.1% per year). In Nicaragua and Panama where rice supplies ~16% and ~24% of dietary energy respectively, the per capita rice harvests could fall due to their population growth [5] outpacing their 0.9% and 0.2% per year rice yield improvement rates (Figure 2b). Elsewhere in the Dominican Republic, Costa Rica, and Haiti, where rice provides 16–22% of their daily dietary energy, yields are declining at rates of −0.1% to −0.6% per year. The per capita rice production is likely to increase only in Cuba, where rice yields are increasing 0.9% per year [31] and the population is projected to fall [5].

Wheat yields are increasing at ~2.4% per year or greater only in some counties in the U. S., (mainly in eastern South Dakota, parts of Nebraska, northeastern Kansas, western Mississippi, and Louisiana) (Figure 2c). Wheat yields are decreasing in many parts of the U. S. Great Plains (Montana, western parts of North Dakota, South Dakota, Kansas and Texas and eastern Colorado). In Mexico, areas with doubling rates in wheat yields are observed only in the state of Zacatecas. Nationally, wheat yields in Canada, United States, and Mexico are increasing at 1.3%, 0.8% and 1.1% per year, respectively.

Most areas in the U. S. show increasing soybean yields, with doubling rates in North Dakota, isolated areas of South Dakota, Nebraska, Mississippi, Louisiana, and Georgia (Figure 2d). Soybean yields are decreasing in Kansas, Oklahoma and Texas. Canada and the United States have yields increasing at 0.2% and 1.2% per year, respectively.

South America

Most maize areas in South America are achieving doubling rates, with the exception of isolated municípios in Brazil. The overall impact of these varied subnational rates is that maize yields are increasing at 1.7–4% per year in Uruguay, Argentina, Chile, and Brazil and may result in significantly higher per capita maize harvests. Other South American countries such as Venezuela, Peru, Bolivia and Ecuador, where maize provides 2–14% of dietary energy, are achieving yield increases of 1.8–3% per year but due to their population growth [5] may result in no significant changes to their per capita maize harvests at least in the short term.

Rice is grown throughout in South America and yields are improving in most areas (Figure 2b). Rice yield rates are at doubling levels however only in the Cesar and Tolima departments of Colombia, and isolated municípios especially in the states of Pará, Maranhão, and Mato Grosso in Brazil and some areas of

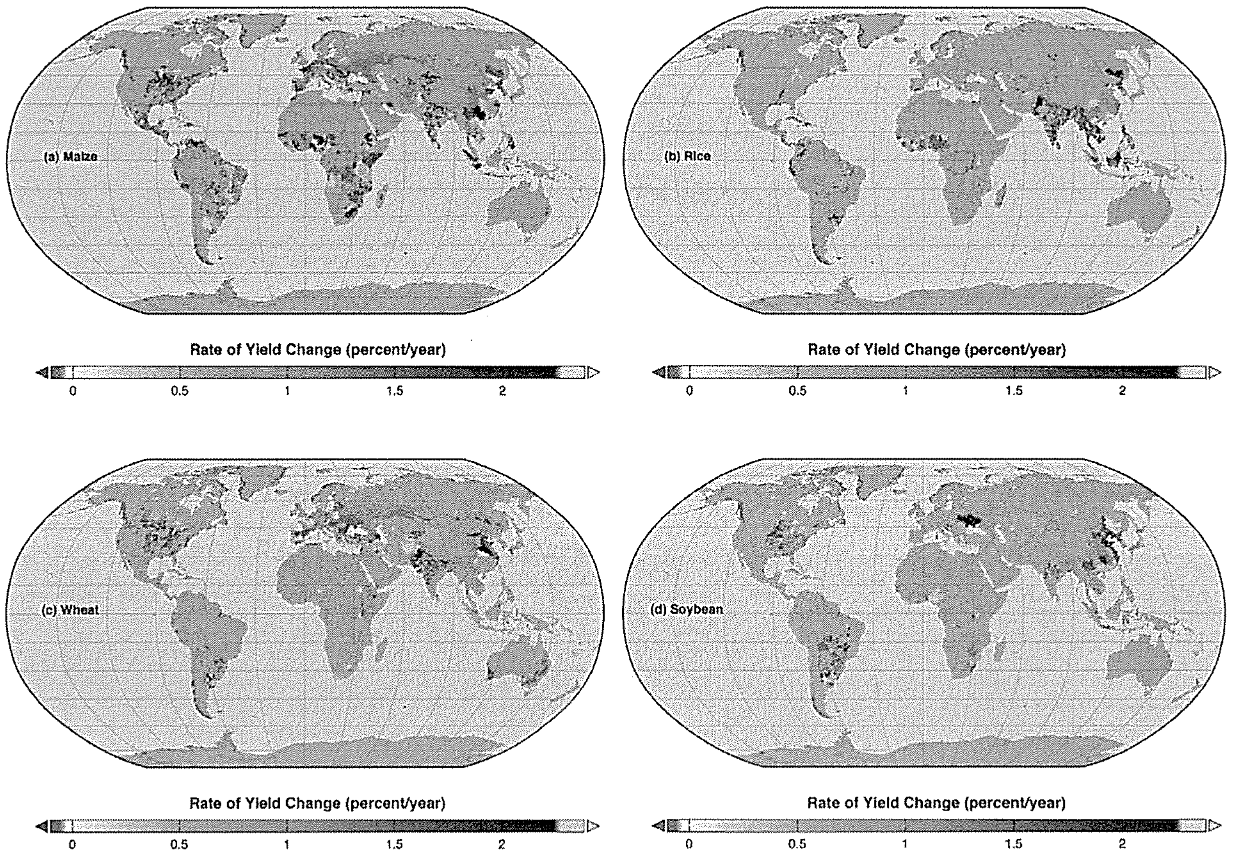

Figure 2. Maps of observed rates of percent yield changes per year. Global map of current percentage rates of changes in (a) maize, (b) rice, (c) wheat, and (d) soybean yields. Red areas show where yields are declining whereas the fluorescent green areas show where rates of yield increase – if sustained – would double production by 2050.
doi:10.1371/journal.pone.0066428.g002

Paraguay, Uruguay and Argentina. Decreasing rates of rice yield are found in northeastern Brazil. The overall impact of these subnational rates of rice yield changes is: national rice yields are improving fast in Brazil, Peru, Colombia, Uruguay, and Argentina (1.6–2.7% per year). But due to population growth [5], yield increases alone may be unable to boost the per capita rice harvested in Peru, Argentina and Ecuador in the short term (~2025). Elsewhere in Venezuela and Bolivia (where rice supplies 8–19% of daily dietary energy and rice yields are improving at 1.1–1.4% per year) per capita harvested rice could remain unchanged to 2050. In Suriname, where rice provides ~25% of dietary energy, the very low rates of rice yield improvement, 0.2% per year, may even lead to decreased per capita rice harvests. In Brazil, Uruguay, Guyana, and Paraguay where rice now supplies ~11%, ~7%, ~29%, and ~2% of dietary energy respectively, the per capita rice harvested could increase.

Large extents of doubling wheat yield rates occur only in Argentina and Chile. Wheat yields are decreasing in parts of Peru and in Santiago del Estero in Argentina. The national trends as a consequence: Argentine and Chilean wheat yields are increasing at 1.5% and 1.9% per year respectively and may result in increased per capita wheat harvests (wheat provided ~25% and ~30% of dietary energy, respectively). In Brazil, Colombia, Ecuador, and Uruguay, yields are increasing at 0.1–1.5% per year and may lead to unchanged per capita harvests, (8–31% of dietary energy is now supplied from wheat in these four countries). Per capita wheat harvests could decrease in: Bolivia, Peru, and Paraguay due to lower yield gains of 0.5–1.6% per year.

With the exception of Bolivia and Paraguay, soybean yields are increasing at doubling rates, particularly in many areas of Argentina, Brazil, Venezuela, and Uruguay. Soybean yields are increasing 1.5–2.4% per year in these countries.

Europe

Almost everywhere in Europe, except in Moldova, maize yields are increasing but rates of ~2.4% per year are found only in Portugal, the Czech Republic, and Belarus. In Moldova, southern Romania (counties in south and southwest region) and Pomeranian province in Poland maize yields are deceasing and have led national maize yields to change at −4.9% per year in Moldova, 0.7% per year in Romania, and 1.1% per year in Poland. Due to rising maize yields of 0.8–3.0% per year, the per capita harvested maize could increase in many European countries by 2050.

Rice is harvested in only a few European countries and yields are increasing at 0.2–1.5% per year. See Data S1 for the numbers.

Wheat is an important food crop in Europe and harvested in almost all European countries. However, in Eastern Europe (Ukraine, Moldova, southern Romania, Bulgaria, parts of Hungary and Slovak Republic), southern France, and northeastern Spain wheat yields are generally decreasing with the exception of a few regions where yield increases are at doubling rates.

Consequently, national wheat yield improvements in European countries are generally <1% per year, with the exception of Estonia (1.5% per year). Even though wheat yield improvements are low, the per capita harvested wheat may increase in some of these European countries because of population declines in Estonia, Germany, Latvia, and Lithuania [5]. Unfortunately, in many other European countries, the low production gains from yield improvement will likely be offset by increasing population, resulting in nearly unchanged per capita wheat harvests. Yields are decreasing in many eastern European countries throughout, where wheat comprises 24–36% of the dietary energy.

Soybean yields are increasing at doubling rates only in small areas in Romania, and in central Italy soybean yields are decreasing. See Data S1 for actual national numbers.

Africa

Africa is a continent of contrasts with regards to rates of maize yield change. For example, maize yields are increasing ~2.4% per year in the Nigerian states of Yobe and Adamawa. Similar maize yield improvement rates are found in some other isolated areas of West African nations, Ethiopia, Angola, South Africa, and Madagascar. But maize yields are decreasing in Morocco, Chad, Somalia, Kenya, Zambia, Zimbabwe, Rwanda, Burundi, and Democratic Republic of Congo. Elsewhere, rates of yield improvement are lower than population growth, suggesting that production per capita is likely to decline. These trends are particularly troubling in countries such as Burundi, Chad, Kenya, Morocco, Rwanda, Democratic Republic of Congo, Somalia, Zambia, and Zimbabwe, where yields are decreasing −0.2% to −7.6% per year, population is rising [5], and maize accounts for 5–51% of calorie intake. The only African countries that may witness an increase in per capita maize harvests due to faster maize yield increases are Angola, Ivory Coast, and Mozambique, where yields are increasing at rates of 2.9%, 4.1%, and 3.2% per year, respectively.

In Ivory Coast, Togo and Benin in West Africa, and in Rwanda, rice yield changes are at doubling rates. In contrast, yields are decreasing more than 1% per year in Gambia and 3% per year in Nigeria. Nearly 8% of the dietary energy in Nigeria is supplied from rice [31]. The per capita rice harvests could decrease in almost all the important rice consuming African nations, e.g., Guinea, Madagascar, Mali, Nigeria, and Tanzania, unless yields are boosted further. Only in Ivory Coast there could be an increase on account of its ~2.6% per year yield increases.

Wheat, while grown in only an extremely small area of Africa, though in many countries, is generally increasing yields at high rates. In Angola, Eritrea Malawi, Nigeria, Algeria, Sudan, and South Africa, yields are growing at doubling rates (2.4–3.4% per year).

In Nigeria, and Mpumalanga province of South Africa soybean yields are increasing at doubling rates whereas in Zimbabwe, Democratic Republic of Congo, and Rwanda yields are decreasing.

Asia and Australasia

Maize yields are generally increasing across Asia. Yield improvement rates are currently on track to double production in some parts of Iran, Pakistan, India, China, Indonesia, Bangladesh, Laos, Cambodia, Vietnam, and Turkey (Figure 2a). In China, Laos, Philippines, Australia, India, Pakistan, and in Turkey, the per capita maize harvested could remain unchanged in the short term but could increase by 2050. In a few countries such as Nepal, Kyrgyzstan, Iraq, Afghanistan, Uzbekistan, and in New Zealand the slower rates of maize yield improvements of 1.3%, 0.3%, 0.9%, 1.1%, 1.6%, and 0.5% per year respectively can result in declines in per capita maize harvests on account of population growth [5]. The per capita maize harvests could increase in Indonesia, Vietnam, Thailand Iran, Myanmar, Bangladesh, Cambodia, Azerbaijan, and in Bhutan [5].

Rice areas with doubling yield rates are found only in some local areas within Afghanistan, India, Bangladesh, Laos, Vietnam and Cambodia. Significant rates of rice yield declines are found in parts of India (especially in parts of Uttar Pradesh, Maharashtra, and Tamil Nadu) and in North Korea. The ~1% per year overall rice yield increase in India could result in no significant change to the overall per capita rice harvested but in China this may remain as only a short term (~2025) problem. Rice provides ~30% and ~27% of the dietary energy in India and China respectively now. On the other hand in the world's third largest rice producer, Indonesia where ~49% of dietary energy is provided by rice, yield improvement rates are much lower at 0.4% per year. The other important Asian rice producers may behave in the following way: no significant change in per capita rice harvests in Pakistan, Nepal, Malaysia, and South Korea; no significant increase in Myanmar, Sri Lanka, Turkey and Bhutan only in the short term, and declines in the Philippines in the long term (~2050). However in Afghanistan, Iraq and Australia due to population growth outpacing production increases from the 2.4%, 0.4%, and 0.3% rates of yield increase per year there could be declines in per capita harvested rice. In North Korea, Kazakhstan, Uzbekistan, and in Turkmenistan yields are declining at −2%, −1.9%, −0.3%, and −1.5% per year respectively. Elsewhere, the per capita rice harvested could increase: Bangladesh, Vietnam, Thailand, Cambodia, Laos, and in Iran due to production increases from high rates of yield improvement (1–2.6% per year) outpacing their population growth [5], and in Japan due to small yield improvement rates (0.5% per year) and small population decreases.

Wheat yields are increasing at doubling rates in parts of Iraq, Iran, and Afghanistan, but only in small parts of the top producing countries of China and India. Wheat yields are decreasing in many areas of India, especially in the states of Madhya Pradesh and Uttaranchal, and in the countries of Kyrgyzstan, and Mongolia, and in the Beijing province of China. Large areas with wheat yield decreases are also found in Queensland, New South Wales, Victoria, and Western Australia, in Australia. The consequence of these wheat yield change rates is diverse. Per capita wheat production could increase in many countries, including China, Iran, and North Korea, because yield increases exceed projected population increases. In contrast, decreases in per capita harvests could occur in: Afghanistan, Georgia, Iraq, Kyrgyzstan, Mongolia, Saudi Arabia, Yemen, and in Australia.

Soybean yields are increasing at ~2.4% throughout China, including the provinces of Jilin, Guangxi, and Guangdong, but are decreasing in Yunnan and Ningxia. Yields are increasing at doubling rates in local areas within Maharashtra in India. In contrast, yields are generally decreasing in the neighboring state of Madhya Pradesh. Doubling rates of soybean yields are also found in Laos and Vietnam, but in North Korea, and Cambodia, yields are decreasing.

Discussion and Conclusions

Numerous studies have shown that feeding a more populated and more prosperous world will roughly require a doubling of agricultural production by 2050 [1–7], translating to a ~2.4% rate of crop production growth per year. We find that the top four global crops – maize, rice, wheat, and soybean – are currently witnessing average yield improvements only between 0.9 to 1.6 percent per year, far slower than the required rates to double their production by 2050 solely from yield gains. This is because yield improvements are below ~2.4% per year in many areas of our most important agricultural lands. At these rates maize, rice, wheat and soybean production may increase by ~67%, ~42%, ~38%, and ~55% respectively, by 2050 globally. There is a 90% chance that the total global production increase from yields alone would be between 34–101% for maize, 21–59% for rice, 4–76% for wheat, and 13–84% for soybean by ~2050. Thus, if these yield change rates do not increase, land clearing possibly would be needed [3] if global food security is to increase or even maintained (Table 1).

We found that the top three rice and wheat producing nations are witnessing very low yield growth rates. China, India and Indonesia are witnessing rice yield increases of only 0.7%, 1.0%, and 0.4% improvement per year. China, India, and the U. S., the top three wheat producers similarly were witnessing yield increases of only 1.7%, 1.1%, and 0.8% per year, respectively. At these rates we found that yield driven production growth in India and China could result in nearly unchanged per capita rice harvests, but decline steeply in Indonesia.

In many of the smaller crop producing nations, maize, rice, or wheat yield improvement rates are below the 2.4% doubling rate. Unfortunately, a high percentage of total calories consumed in these countries are from these four crops. This is particularly true for maize throughout much of Africa (e.g., Kenya, Zambia, Zimbabwe), Central America (e.g., Guatemala, Nicaragua, Panama), and parts of Asia (e.g., Nepal, Georgia).

Rice provides ~19% of dietary energy globally. Rice provides a higher percentage of total calories consumed in countries such as Dominican Republic, Costa Rica, Haiti, Sierra Leone, Nigeria, and North Korea, yet yields are declining, −0.1% to −3.2% per year. Elsewhere rice yields are increasing too slowly to overcome the impact of their population growth. In some of the world's top rice producers, e.g. India and China, the per capita production may remain nearly unchanged. In numerous smaller rice producers across the world where rice is an important significant provider of daily dietary energy such as in Peru, Ecuador, Bolivia, Benin, Togo, Myanmar, Philippines, Malaysia, South Korea, Nepal, and in Sri Lanka, the per capita production may also remain unchanged.

Wheat provides ~19% of global dietary energy. Wheat comprises an even larger portion of the diet in some countries where yields are declining, particularly Eastern European countries of Bulgaria, Hungary, Czech Republic, Moldova, Romania, Slovakia, and Ukraine. In many countries, such as Bolivia, Peru, Paraguay, Afghanistan, and Iraq, wheat yield increases are too low to maintain their current per capita harvests.

Our analysis identifies where yield improvements are on track to double production and where investments should be targeted to increase yields. The observed rates of yield change result from several location-specific, socio-economic, and biophysical factors that are described elsewhere [23]. Many studies illustrate that intensification can be unsustainable [32–36], but several notable projects in Africa [37] and elsewhere [38] have shown that sustainable intensification is possible and necessary to boost global crop production.

Clearly, the world faces a looming and growing agricultural crisis. Yields are not improving fast enough to keep up with projected demands in 2050. However, opportunities do exist to increase production through more efficient use of current arable lands [4] and increasing yield growth rates by spreading best management practices and closing yield gaps under different management regimes [38–42] across the globe. A portion of the production shortfall could also be met by expanding croplands, but at a high environmental cost to biodiversity and carbon emissions [4,43–45]. Alternatively, additional strategies, particularly changing to more plant-based diets and reducing food waste [4,46–48] can reduce the large expected demand growth in food [3,4].

Methods

Data

We used annual crop census reports for harvested areas and yield from ~13,500 political units globally covering 20 years from 1989 to 2008 in this analysis though the database itself covers the years 1961 to 2008. The sum total of these census reports for the 20 years was approximately 1.8 million. Data were collected at three political levels/units depending on data availability: country, state/provinces, and county/district/municipio/department. Data were not available for all political units for each year. Details of the number of years data was available and its source is given in the Table S1. For the political units where data was missing for some years we estimated crop harvested and yield information using the average of the latest five years of reported data and constraining them with the reported numbers from the higher political unit as explained further in Text S1 and previous work [23].

Population data and its projections per country were from the United Nation's medium variant projections [5]. Crop production was determined using the projected crop yields at current observed rates of yield change and harvested areas fixed at ~2007. Per capita harvested production is the ratio of production to population and a greater than ±10% change from ~2007 is considered as significant either in the short- (2025) or long-term (2050).

Analysis

We linearly regressed 20 years of crop yields at each of the political units to determine the average linear rates of yield improvement over the observed period. Many previous studies have shown that crop yields change linearly and have used linear regression to project future crop yields [24–30]. Here we calculate the non-compounding linear percentage rate by solving a in Equation 1; Y is the yield in the year 2008, $2Y$ is the yield in 2050 (after *42* years):

$$2Y = \frac{a * Y * 42}{100} + Y \qquad (1)$$

This gives a rate of 2.38% per year or approximately 2.4% per year. For reported numbers at the local- to country- to global-scale the linear percentage changes are the observed changes using 2008 yields as the base year. The actual changes are provided in Data S1 for each crop and country.

Details of the method used, sensitivity to the number of years analyzed, as well as alternate regression methods are provided in Figures S6 and S9. The advantage of analyzing at high spatial resolution is that yield rates can be summarized for other unique levels. For example, we summarized the results for the Brazilian Legal Amazon (Figure S12 and Table S2). We compared our global numbers with other reported estimates. These comparisons are provided in Table S3.

Supporting Information

Figure S1 Global maps of the coefficient of variation (r^2) for maize, rice, wheat, and soybean when fitted to 20 years of yield information at each political unit analyzed.
(TIFF)

Figure S2 Global maps of normality of the data for maize, rice, wheat, and soybean at each political unit analyzed from the Lilliefors test (green colors show where the normality assumptions are not violated at $p>0.05$ and red colors where they are violated at $p\leq 0.05$).
(TIFF)

Figure S3 Global maps of autocorrelation of the data for maize, rice, wheat, and soybean at each political unit analyzed from the Durbin-Watson test (green colors show where the autocorrelation assumptions are violated at $p>0.05$ and red colors where they hold at $p\leq 0.05$).
(TIFF)

Figure S4 Diagnostic plots for a linear fit ($r^2 = 0.49$, $p<0.01$) to soybean yield data in the United States. Subplots show a) model fit and standard 95% confidence interval, b) QQ plot, c) residuals versus fitted values, and d) residuals versus lagged residuals. Durbin-Watson test for autocorrelation: $p = 0.66$. Lilliefors test for normality of yield data: $p>0.5$.
(TIFF)

Figure S5 Diagnostic plots for a linear fit ($r^2 = 0.49$, $p<0.01$) to maize yield data in Angola. Subplots show a) model fit and standard 95% confidence interval, b) QQ plot, c) residuals versus fitted values, and d) residuals versus lagged residuals. Durbin-Watson test for autocorrelation: $p<0.05$. Lilliefors test for normality of yield data: $p>0.5$.
(TIFF)

Figure S6 Parsimoniously fitted yields at each of the political units and using them to project global crop yields to the year 2025.
(TIFF)

Figure S7 Diagnostic plots for a quadratic fit ($r^2 = 0.60$, $p<0.01$) to maize yield data in Angola. Subplots show a) model fit and standard 95% confidence interval, b) QQ plot, c) residuals versus fitted values, and d) residuals versus lagged residuals. Durbin-Watson test for autocorrelation: $p = 0.08$.
(TIFF)

Figure S8 Consequences of extrapolating linear and quadratic maize yield models for Angola to 2050.
(TIFF)

Figure S9 Global maize, rice, wheat, and soybean yield fitted to 15 and 25 years of data and using it to project yields to the year 2025. Dashed lines correspond to analysis using 15 years of data (1994–2008), dotted lines correspond to using 25 years of data (1984–2008), and solid lines correspond to using 20 years of data (1989–2008). Due to the similarity in results in some cases all lines are not clearly distinguishable from each other always.
(TIFF)

Figure S10 Rates of yield change in kg/ha/year/year.
(TIFF)

Figure S11 Year 2008 yields.
(TIFF)

Figure S12 Similar to Figure 1 in the main text but only for the Brazilian Legal Amazon.
(TIFF)

Table S1 Country data source, number of political units analyzed per country, time frame and number of official statistics collected per crop for the period 1989 to 2008.
(DOCX)

Table S2 Current yields, projections and production for the Brazilian Legal Amazon.
(DOCX)

Table S3 Comparison with the future U. S. crop yields reported by the USDA-ERS [91] (maize, wheat, and soybean were reported in bushels per acre, rice in pounds per acres from USDA-ERS and converted to ton/ha), and global wheat yields reported by the FAO-OECD [90].
(DOCX)

Text S1 Additional Data, Model Fitting, Rates, and Inter-comparison information.
(DOC)

Data S1 Rates observed for each crop and country.
(XLSX)

Acknowledgments

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Author Contributions

Conceived and designed the experiments: DKR JAF. Performed the experiments: DKR. Analyzed the data: DKR NDM PCW JAF. Contributed reagents/materials/analysis tools: DKR NDM JAF. Wrote the paper: DKR NDM PCW JAF.

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WWF LIVING FORESTS REPORT: CHAPTER 4

FORESTS AND WOOD PRODUCTS

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FORESTS AND WOOD PRODUCTS

This chapter of the Living Forests Report explores how we can meet future demand for wood products within the finite resources of one planet.

The *Living Forests Report* aims to catalyse debate on the future role and value of forests in a world where humanity is living within the Earth's ecological limits and sharing its resources equitably. The report presents **Zero Net Deforestation and Degradation** (ZNDD) by 2020 as a target that reflects the scale and urgency with which threats to the world's forest biodiversity and climate need to be tackled. We use the **Living Forests Model**[1], developed by WWF in collaboration with the International Institute for Applied Systems Analysis (IIASA), to look at the land-use implications of ZNDD under a range of scenarios that consider different conservation, dietary and energy-use options.

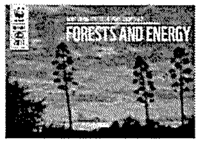
The first three chapters of the report were published in 2011:

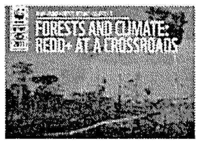
Chapter 1 – ***Forests for a Living Planet*** examines the drivers of deforestation and the need to shift to a new model of sustainable forestry, farming and consumption with ZNDD.

Chapter 2 – ***Forests and Energy*** examines the safeguards needed to ensure expanding use of **bioenergy** helps to provide energy security, rural development and greenhouse gas (**GHG**) reductions without destroying valuable ecosystems or undermining food and water security.

Chapter 3 – ***Forests and Climate* – REDD+ *at a Crossroads*** highlights REDD+ as a unique opportunity to cut GHG emissions from forests in time to prevent runaway climate change, but only if investments are made now.

Zero Net Deforestation and Forest Degradation (ZNDD): WWF defines ZNDD as no net forest loss through deforestation and no net decline in forest quality through degradation. ZNDD provides some flexibility: it is not quite the same as no forest clearing anywhere, under any circumstances. For instance, it recognizes people's right to clear some forests for agriculture, or the value in occasionally "trading off" degraded forests to free up other land to restore important biological corridors, provided that biodiversity values and net quantity and quality of forests are maintained. In advocating ZNDD by 2020, WWF stresses that: (a) most natural forest should be retained — the annual rate of loss of natural or semi-natural forests should be reduced to near zero; and (b) any gross loss or degradation of pristine natural forests would need to be offset by an equivalent area of socially and environmentally sound forest restoration. In this accounting, plantations are not equated with natural forests as many values are diminished when a plantation replaces a natural forest.





This 4th chapter examines current and future demand for wood products and how this can best be met. We explore the many values and uses of **wood** and its footprint relative to alternative materials (**pages 2-7**); the current and future demand for wood products (**pages 8-17**); the relationship between wood production and the conservation of other forest values (**pages 19-21**) and various options for producing wood (**pages 22-31**). The chapter concludes with broad solutions that will enable humanity to optimize the use and benefits of wood without diminishing the natural capital in the world's forests.

While this chapter focuses on wood as the major commodity extracted from forests, it is important to note that forests also produce **non-timber forest products** (NTFPs). The global value NTFPs is hard to assess but was estimated at US$18.5 billion in 2005[2]. The economic, cultural and ecological value of NTFPs makes them an important component of sustainable forest management and the conservation of biological and cultural diversity.

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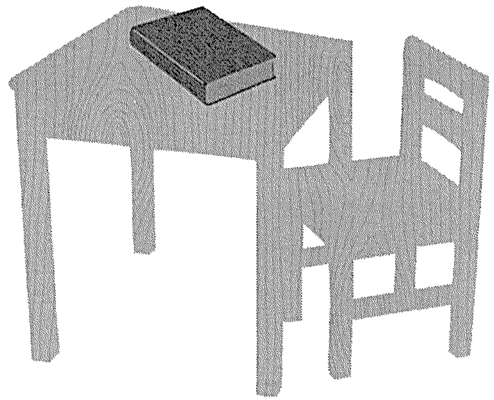
WOOD PRODUCTS: TODAY AND TOMORROW

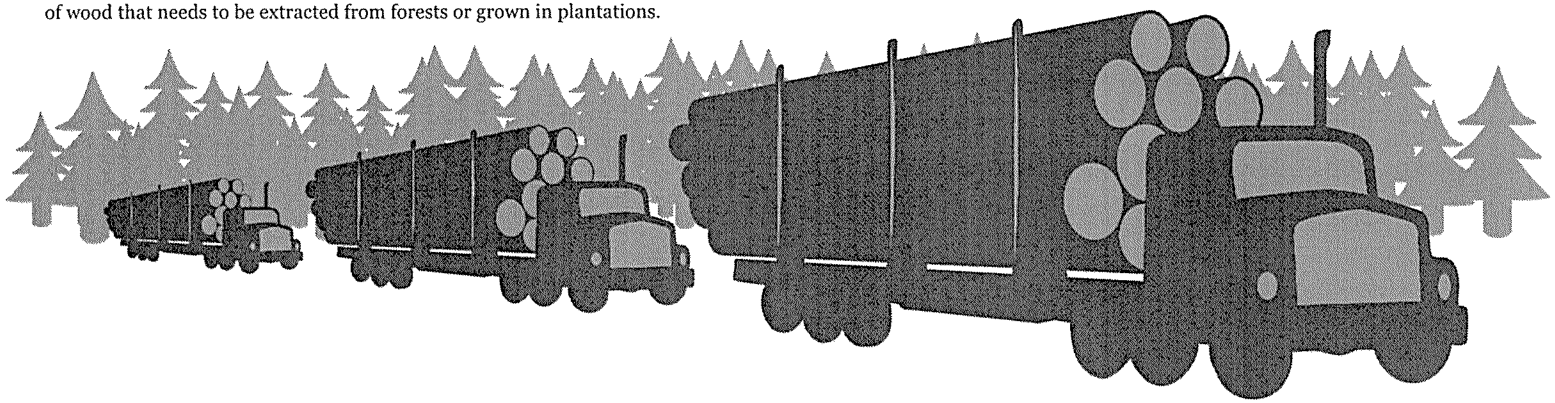
Humanity will likely use more wood in more ways as the future unfolds. If **production forests** are managed sustainably and wood products are used efficiently or replace others with a heavier footprint, this should be good for the planet.



WWF advocates reducing wasteful consumption of wood and **paper**. But even with more frugal use and greater efficiencies, net demand is likely to grow with rising population and incomes in developing countries. So how can we produce more wood without destroying or degrading forests, in a world where competition for land and water is increasing? This challenge spans the whole supply chain, from where and how wood is grown and harvested to how wisely and efficiently it is processed, used and reused. It also involves changes to consumption patterns – such as eliminating excessive and wasteful use of paper in rich societies, while improving access for the poor to paper products that can improve education, hygiene and food safety.

EVEN WITH MORE FRUGAL USE AND GREATER EFFICIENCIES, NET DEMAND IS LIKELY TO GROW

Advancing technology is enabling new uses of wood and its core chemical components in composites, films and chemically processed speciality **cellulose**. In the future such uses could add significantly to the volume of wood that needs to be extracted from forests or grown in plantations.



THE MANY LIVES OF WOOD

A single piece of wood or wood fibre can be recycled through a succession of different products.

Nearly all types of solid wood can be reused if recovered and separated from other waste. Wood can be salvaged from old buildings, bridges and wharfs and used again in modern décor, from furniture to flooring. Smaller, less valuable wood scraps can be collected and used to make particle board and other modern composite products. In the UK, more than half of the wood previously sent to landfill is now recycled[13].

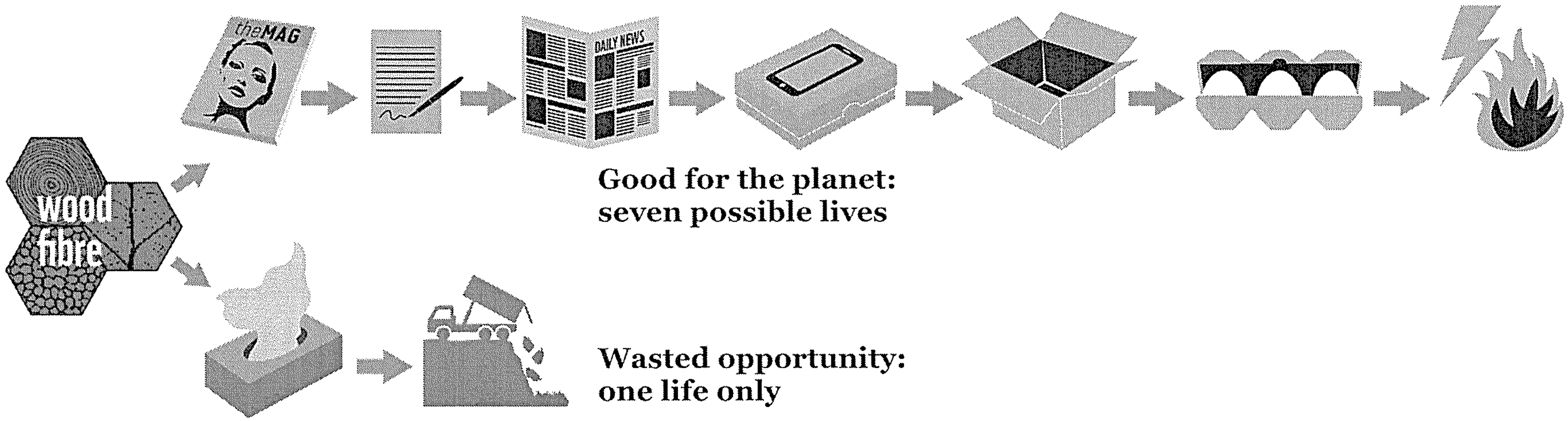
Paper can be recycled and reused many times, thus reducing the volume of virgin wood fibre needed to produce paper products.

This recycling flow can be shortened if paper is prematurely burned or dumped in landfills. In 2010, 28.5 per cent of the 227 million tonnes of municipal waste generated in the US was paper and paperboard[14].

The proportion of virgin wood fibre that needs to be added at each recycling stage depends on the product quality requirements, for example, virgin wood fibres tend to be stronger, longer and produce whiter paper than those that have been recycled several times. Technologies are under development for a very short wood fibre that can be used even beyond the seven uses shown below.

Paperboard: a relatively stiff, heavy material, thicker than paper, that is produced by pressing together moist fibres, typically derived from pulpwood, fibre crops or recovered paper, and drying them into thick sheets.

The many lives of a wood fibre



THE DEMAND FOR WOOD PRODUCTS

The Living Forests Model projects significant growth in wood removals to meet rising demand for wood products.

In 2010, global reported wood removals[15] amounted to 3.4 billion m³. Total removals were undoubtedly higher due to illegal or unreported wood harvesting, especially fuelwood. Of the reported harvest, 1.5 billion m³ was used as industrial roundwood and the rest for fuelwood[16].

The Living Forests Model (see figure) projects annual wood removals in 2050 will be three times the volume reported for 2010. The projection includes steadily growing demand for solid wood and paper products between now and 2050 in emerging markets. However, a projected massive escalation in use of wood as a feedstock for bioenergy is the main driver of rising demand. The Living Forests Model projects that by 2050, annual demand for **energy wood** (woody biomass that is not used for household fuelwood or the production of wood-based products) alone will exceed 6 billion m³ under the **Do Nothing scenario** and 8 billion m³ under the **Bioenergy Plus scenario** (the latter projection is more than double the total reported wood removals in 2010)[17].

The Living Forests Model projections are based on certain assumptions, and should not be read as an attempt to forecast the future, given the many uncertainties that will affect future demand and supply. For example, the model does not attempt to factor in potential, but currently unknown, uses of wood spurred by future technological innovation, nor does it assume dramatic shifts in consumption patterns or recycling rates. However, the model does highlight the likelihood of steady growth in overall volume of virgin wood for products and the potential for dramatic growth in the volume of wood harvested for use as energy "and to reach ambitious carbon mitigation targets under the Bioenergy Plus scenario[18].

Bioenergy Plus scenario: a scenario of the Living Forests Model where bioenergy feedstock demand is based on the "global 2°C scenario" derived from the POLES (Prospective Outlook for the Long-term Energy System) model .

Do Nothing Scenario: A Living Forests Model projection of what the world could look like if our behaviour continues in line with historical trends. The Do Nothing Scenario anticipates land-use change due to: (a) demands for land to supply a growing global human population with food, fibre and fuel; and (b) continuation of historical patterns of poorly planned and governed exploitation of forest resources. Key assumptions in this scenario are:

- By 2050, world population reaches 9.1 billion and per-capita GDP almost triples.
- Demand for commodities is driven by changes in affluence (measured by GDP) and human population growth.
- Aggregate historical trends in agricultural productivity gains continue.
- The average human diet in a country changes according to historically observed relationships with per-capita GDP.
- Forestry and agricultural production does not expand into protected areas, but unprotected natural habitats can be managed for production of timber or converted to timber plantations, cropland and pasture.
- Total primary energy use from land-based biomass feedstocks doubles between 2010 and 2050 due to projected energy demand and the competitiveness of bioenergy technologies and supply chains.

En wo tha for fue prc wo prc

Saw logs & veneer logs	853	1,444	1,444	1,763	1,773
Pulpwood*	527	754	754	905	893
Other industrial roundwood[19]	153	153	153	153	153
Energy wood	1,868	2,753	3,138	6,317	8,209
Household fuelwood		2,064	2,064	2,218	2,054
Total wood supply	3,401	**7,168**	**7,553**	**11,356**	**13,082**

Units: millions of cubic metres (roundwood equivalent)

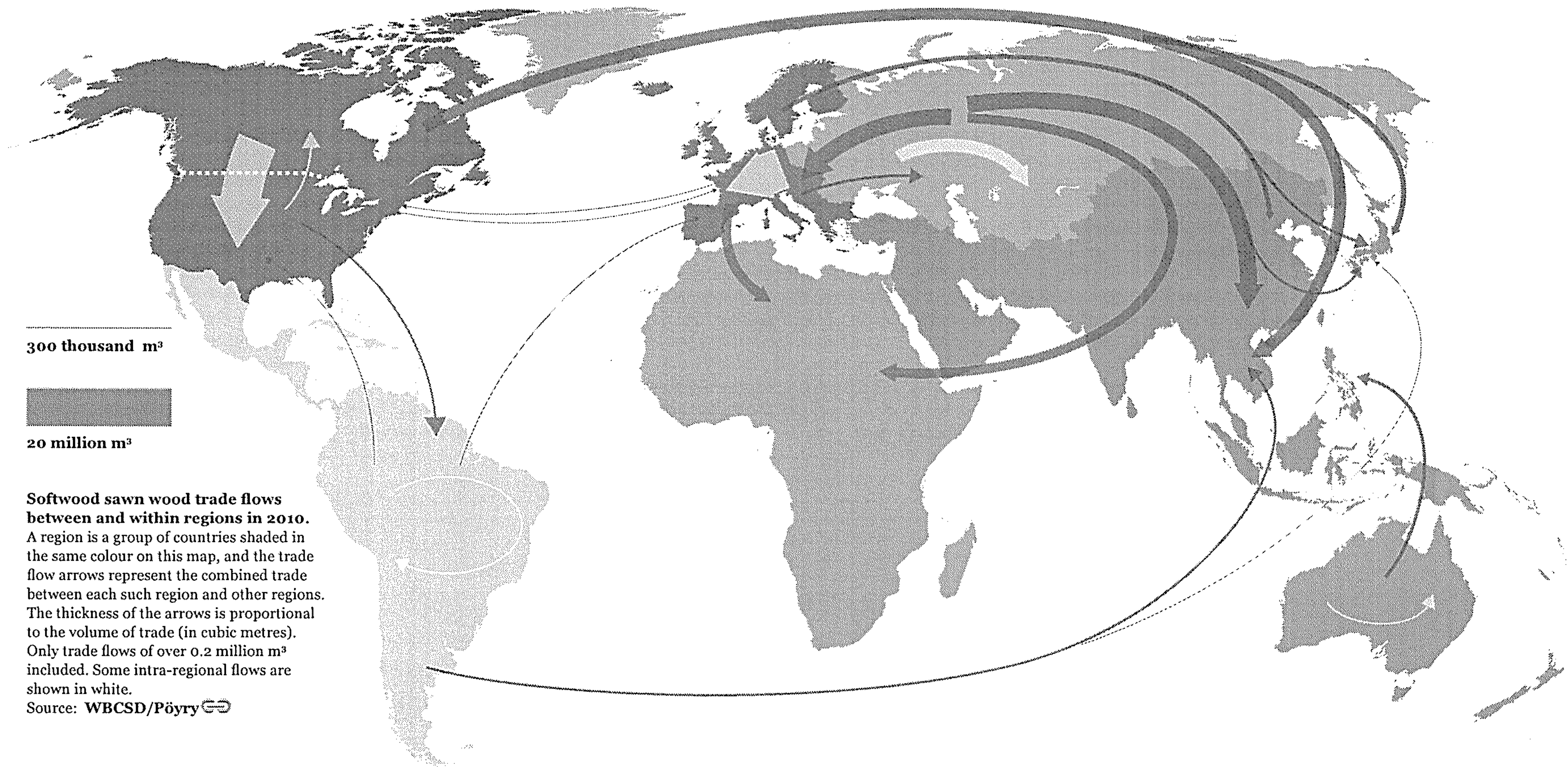
Projected annual rate of wood removals in 2030 and 2050 under the Living Forests Model's Do Nothing and Bioenergy Plus scenarios compared to FAO statistics on reported wood removals in 2010. Source: FAO (2010 figures20) and IIASA (2030 and 2050 projections)

* Pulpwood does not include offcuts and sawdust from saw logs that are used in significant amounts in pulp production.

TRADE IN SAWN WOOD AND PANEL PRODUCTS

The major regions importing sawn wood and panels are Asia, North America and Western Europe, although Africa and the Middle East are fast emerging as major destinations.

The increased demand for sawn wood and panels could compound the pressure on forests in WWF priority places such as the Amazon and Guianas, Chocó-Darién, Sumatra, Atlantic Forests, Altai-Sayan Montane Forests, Borneo, Mekong Complex, Southwest Australia, Congo Basin, Amur-Heilong, Yangtze Basin, Southern Chile, Coastal East Africa and the Mediterranean.



Softwood sawn wood trade flows between and within regions in 2010. A region is a group of countries shaded in the same colour on this map, and the trade flow arrows represent the combined trade between each such region and other regions. The thickness of the arrows is proportional to the volume of trade (in cubic metres). Only trade flows of over 0.2 million m³ included. Some intra-regional flows are shown in white.
Source: **WBCSD/Pöyry**

WHERE IS PAPER MADE AND CONSUMED?

Around 40 per cent of the annual industrial wood harvest is processed to make paper and paperboard.

The volume of wood used in this production has doubled since the 1960s. Paper and paperboard production has increased fourfold in the same period, through increased wood harvest and use of **recovered paper**[21].

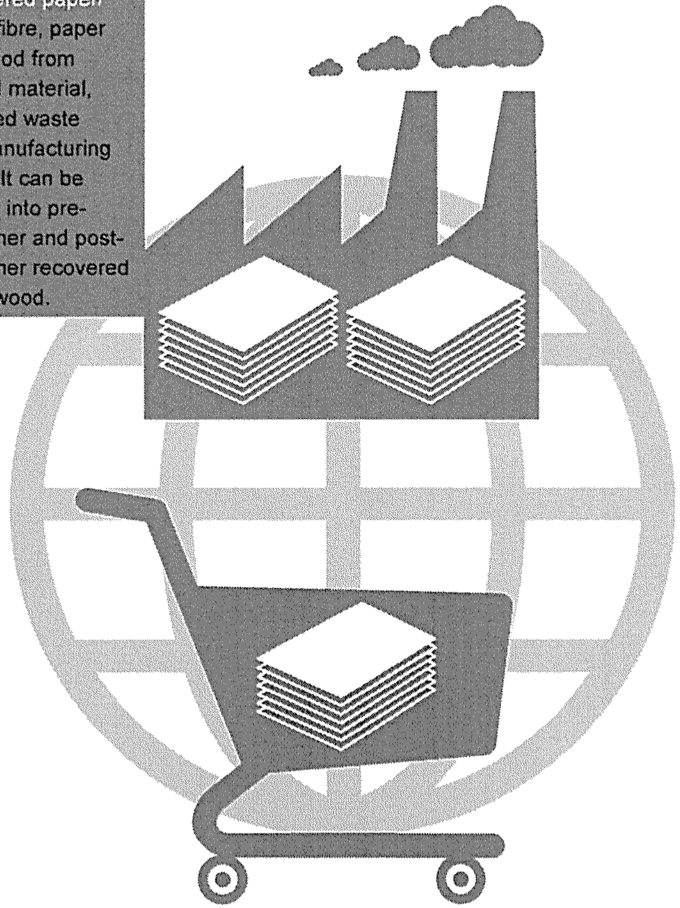
As shown in Figure A, Page 12, the main paper consuming countries/regions are China, the US, Japan and Europe (mainly Germany, Italy, UK, France)[22]. While China appears to be consuming most of its paper production, this statistic masks that as much as a quarter is exported as packaging for manufactured goods and in finished products that use paper (e.g., in instruction manuals)[23]. Most analysts anticipate a continuing shift in trade patterns due to faster-growing demand in emerging markets. The highest long-term demand growth for paper is expected in packaging (wrapping paper, containers and cartons) and tissue[24]. Demand for printing and writing papers has lower expected growth – even declining in some regions, leading to a lower net demand for wood pulp in North America, Japan and Western Europe.

Market pulp: pulp that is produced in one location, from virgin or recycled fibre, dried and shipped to another location for further processing to make paper and paperboard.

Trade in **market pulp** is growing steadily as more paper products are produced away from the wood supply. This is associated with a trend to locate paper mills closer to the end customer (for example, to supply specialized products tailored to the buyer's needs) or in countries with comparative advantage in manufacturing (e.g., China).

The increased demand for virgin wood fibre for pulp and paper and the related wood pulp trade (see map on next page) could compound the pressure on forests in WWF priority places such as Sumatra, New Guinea, Southern Chile, Amur-Heilong, Altai-Sayan, Chocó-Darién, Atlantic Forests and Borneo.

Recovered paper/wood: fibre, paper and wood from unused material, collected waste and manufacturing waste. It can be divided into pre-consumer and post-consumer recovered paper/wood.



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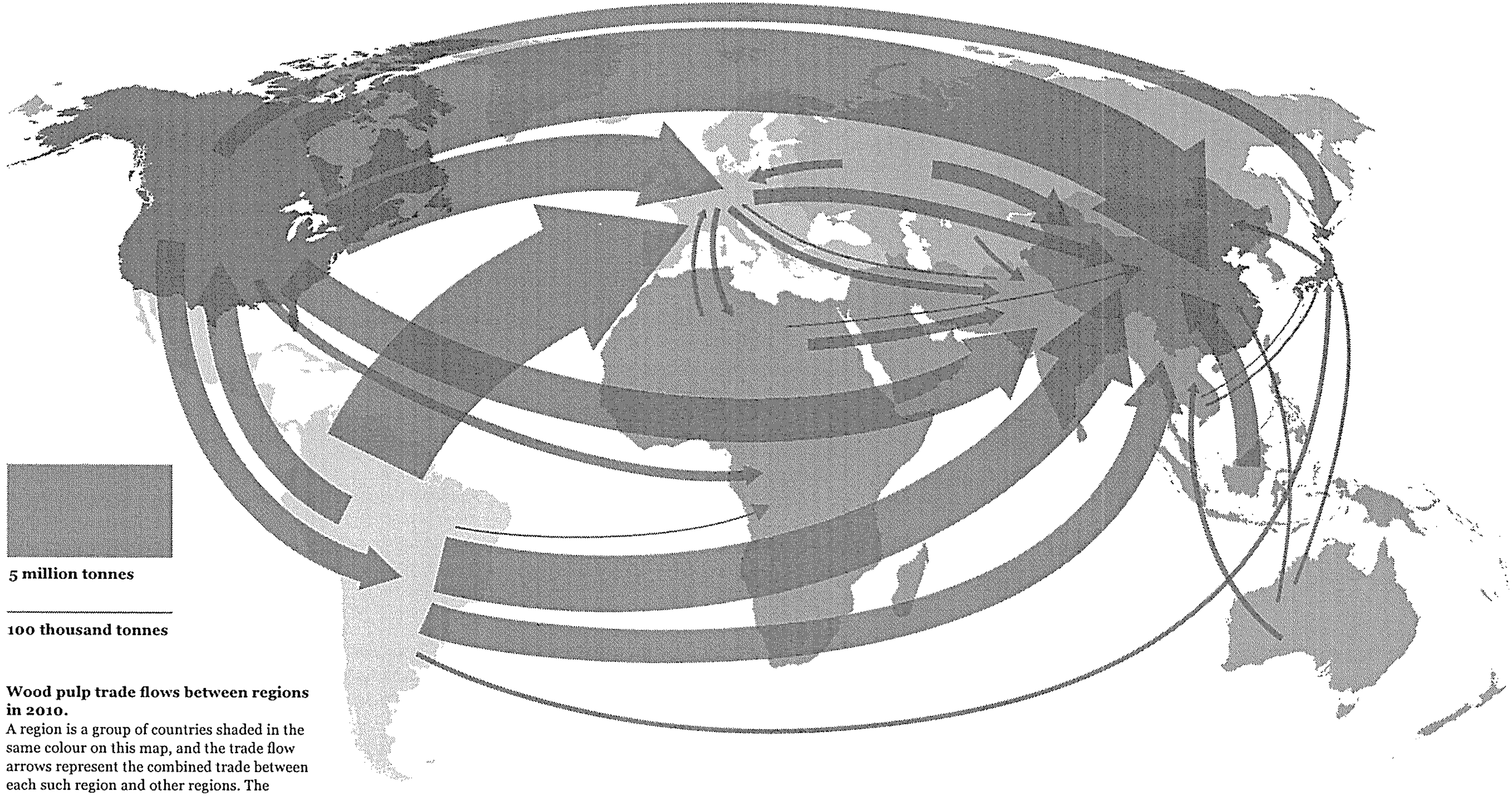
GLOBAL WOOD PULP TRADE FLOW



Wood pulp trade flows between regions in 2010.
A region is a group of countries shaded in the same colour on this map, and the trade flow arrows represent the combined trade between each such region and other regions. The thickness of the arrows is proportional to the volume of trade (in tonnes). Intra-regional flows and flows below 100,000 tonnes are excluded.
Source: **WBCSD/Pöyry**

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PAPER CONSUMPTION AND PRODUCTION

In 2009, China (24 per cent) and the US (19 per cent) were the world's biggest paper and paperboard producers[25]. North America and the Nordic countries have built very few new production lines in the past 15-20 years and will decrease production in the future, while Asia's production is expected to increase (see figure A). According to WBCSD/Pöyry estimates[26], the main paper-producing region in 2025 (see figure B) will be Asia ahead of North America and Western Europe. Increased demand for wood pulp and recovered paper is projected in China, the rest of Asia, Eastern Europe and Latin America.

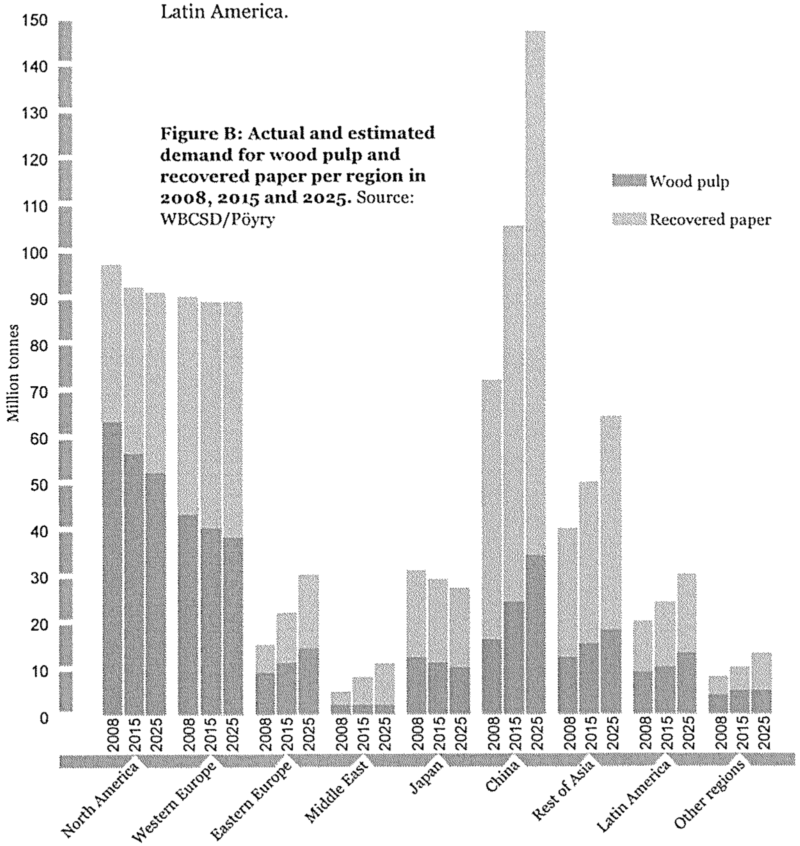


Figure B: Actual and estimated demand for wood pulp and recovered paper per region in 2008, 2015 and 2025. Source: WBCSD/Pöyry

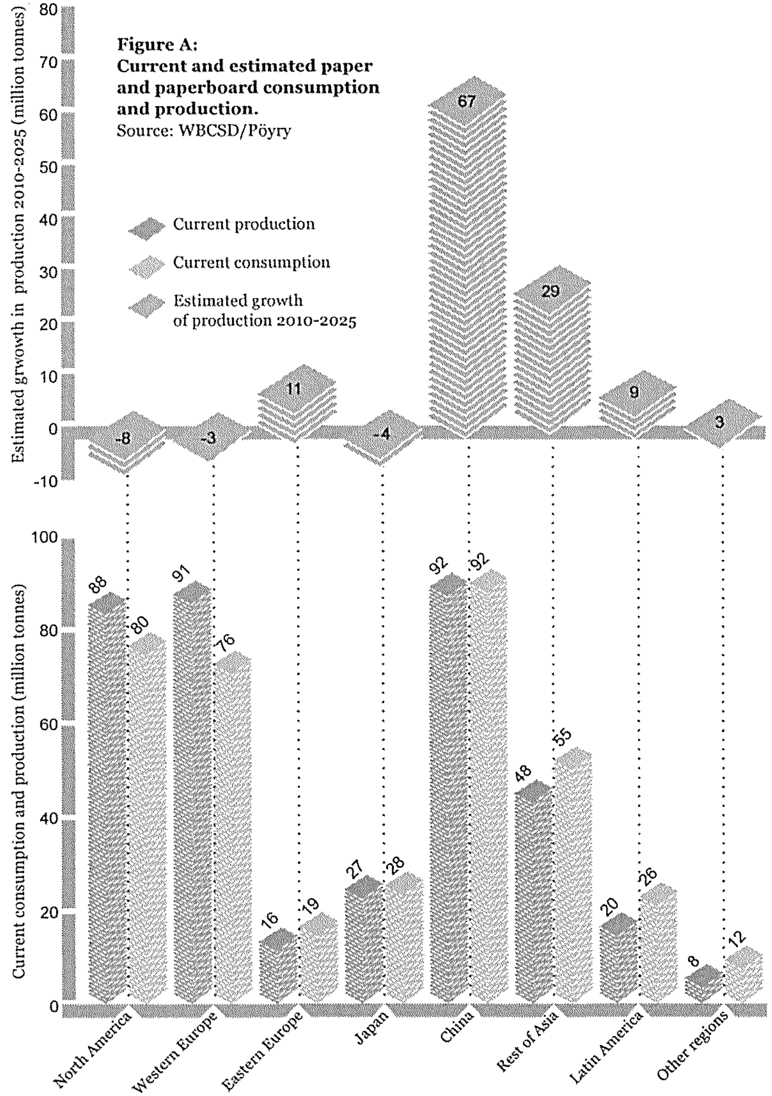
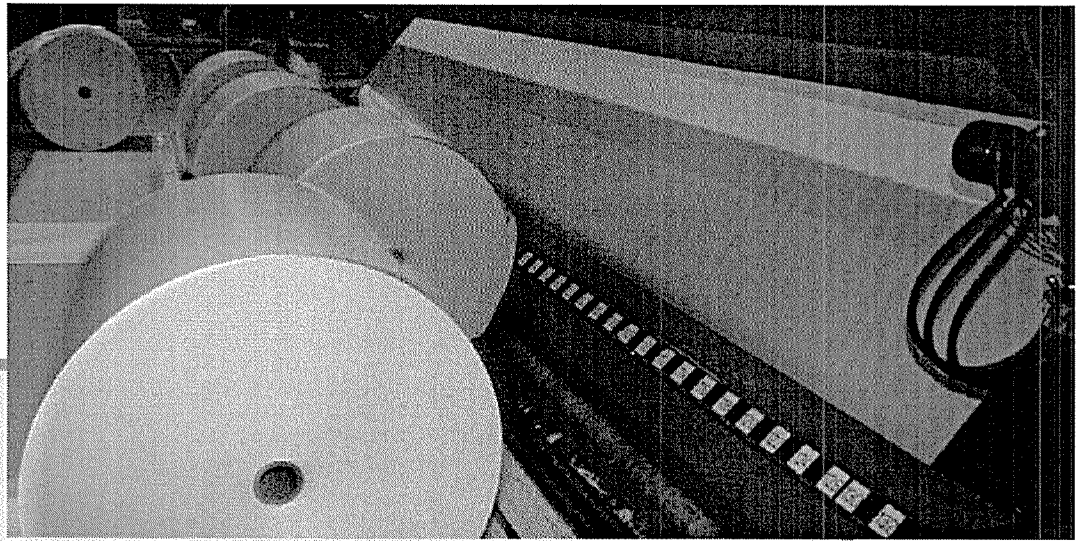


Figure A: Current and estimated paper and paperboard consumption and production. Source: WBCSD/Pöyry

TALKING POINT: AN INDUSTRY VIEW



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Paper produced from a certified forest in Sweden.

The forest industry has a long history of change and expansion, from papyrus to Gutenberg and modern paper machines and bio-refineries. It now stands before another period of change and transition. There are three main foundations for the success of this change: sustainable management of a renewable raw material in natural forests and plantations; new processes and technologies; and, finally, new types of bio-based products for the consumer.

In sustainable forest management, consistent work in developing methods, equipment and certification for forests in all corners of the world is bearing fruit. The integration of new harvesting technology, new models for plantation forestry, new programmes to extend the use of environmental best practices, new ways of addressing social issues and the assurance, education and technology transfer benefits of independent certification are bringing results with accelerating speed – in conserving biodiversity, for instance.
New technologies are being developed by the industry and equipment manufacturers, including more material- and energy-efficient processes and advances such as nanotech coating, new pulping methods, and engineered wood building systems. This increasingly happens in cooperation with the end product part of the chain. The new high-tech wood-based solutions will leave a significantly lower ecological footprint than alternative materials.

In new products, the industry enters even deeper into the consumer's day-to-day with bio-based materials, biofuels and bio-based chemicals, leading to new alliances. Among others, the automotive, pharmaceutical, cosmetics, textiles, electronics and food sectors are becoming a closer part of the forest industry's network.

The forest-based industry is central to a new low-carbon economy. Wood-based products can substitute for many less sustainable, non-renewable alternatives. Forests represent the best investment option for large-scale carbon storage.

Sustainable forest management is the key strategy for producing more fibre. Innovation, including through biotechnology, will also be essential for expanding the sustainable supply of biomass in a resource-limited world. Using this fibre wisely as a foundation of a bio-based economy is a significant sustainable development opportunity.

All in all, the forest industry is embracing this change as an opportunity. In an age of resource scarcity, its sustainable, renewable, material-efficient products are ideally placed to satisfy the needs at the heart of the consumer's daily life.

José Luciano Penido, Chairman, Fibria and Riikka Joukio, Senior Vice President, Metsä Group; Co-chairs, WBCSD Forest Solutions Group

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IMPACT OF RECYCLING ON OVERALL DEMAND FOR WOOD

Increasing the proportion of recycled material in wood products can reduce demand for virgin wood fibre and increase the net value of wood.

Use of material other than virgin wood fibre for the production of sawn wood, panels and paper increased from 21 per cent of total fibre use in 1990 to 37 per cent in 2010 and is projected to reach almost 45 per cent in 2030[27]. Recovered paper is the largest source, then **non-wood fibre**, but collection of waste wood products (demolition waste, used furniture, etc.) is increasing rapidly, as is use of recycled wood in board production.

In 2010, recovered paper comprised 53 per cent of the fibre used in global paper production, increasing from 43 per cent in 2000[28]. Virgin fibres make up the other 47 per cent, including 4.7 per cent from non-wood sources (e.g., bamboo, agricultural residues, etc.)[29]. Non-wood fibres are used extensively in India, for example, and if sourced from sustainably managed areas could help reduce the footprint on forests.

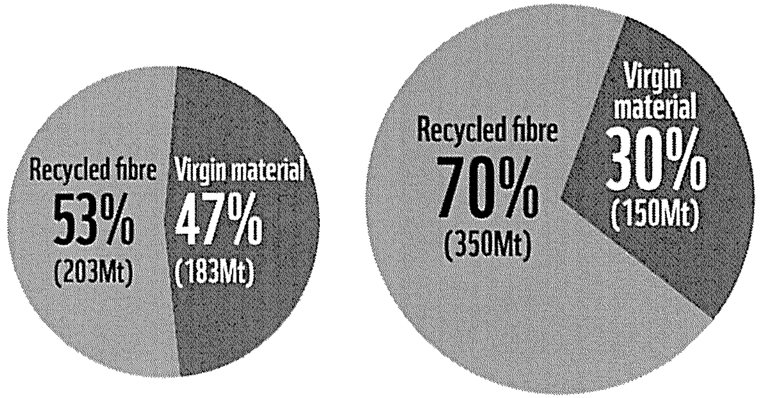
Paper recovery and use vary greatly between countries. China alone imported 50 per cent of the recovered paper that was internationally traded in 2009[30]. Recovered paper use will further grow in the future. A scenario developed by Voith[31] (see figure) indicates that even with higher global paper consumption, demand for virgin material (both wood and non-wood) would drop if global use of recovered paper increased. In theory, this would reduce the share of the world's forests and land that needs to be allocated to fibre production for the paper industry.

Increased recycling involves sorting and separating paper products from other waste. A **recovery rate** of 90 per cent was reached by South Korea in 2009. Efforts to increase recycling are likely to have the greatest impact on the overall footprint of the paper industry if targeted at countries with low recovery rates and increasing consumption; reducing the distance that recovered paper is transported for recycling would also have a significant effect.

Non-wood fibre: cellulose-filled cells that are extracted from biological material other than wood (e.g., bamboo, agricultural residues) and used to manufacture a variety of products including paper.

Recovery rate: percentage of usable recycled materials that have been removed from waste generated in a specific area or by a specific industry.

Producing more paper with less virgin material



2010: 400 million tonnes paper produced

2020 scenario: 500 million tonnes paper produced with 70% recycled fibre

Recycled fibre | Virgin material

Increased paper recycling and improved paper-making technologies could reduce the demand for virgin material by 2020. The ratio of different fibre sources (in % and volume) for worldwide production in 2010 (source: FAO[33]) and under a scenario for the year 2020 (source: Voith[34]).

Trends in the mix of paper products consumed will affect the prospects for increased recycling. **Recycled fibres** make up almost 80 per cent of fibre in **container boards**, but barely 10 per cent of fine printing paper, for instance. Consumer preferences are another key factor. For example, increased consumer demand for recycled content could erode the market for pure-white tissues, motivating the makers of these throwaway products to use more recycled fibre – today's global average for recycled fibre in tissue products is 50 per cent[32].

Container board: container board is a type of light-weight paperboard specially manufactured for the production of corrugated board (formed by gluing one or more fluted sheets of paperboard to one or more flat sheet). It is typically used in the packaging of large materials.

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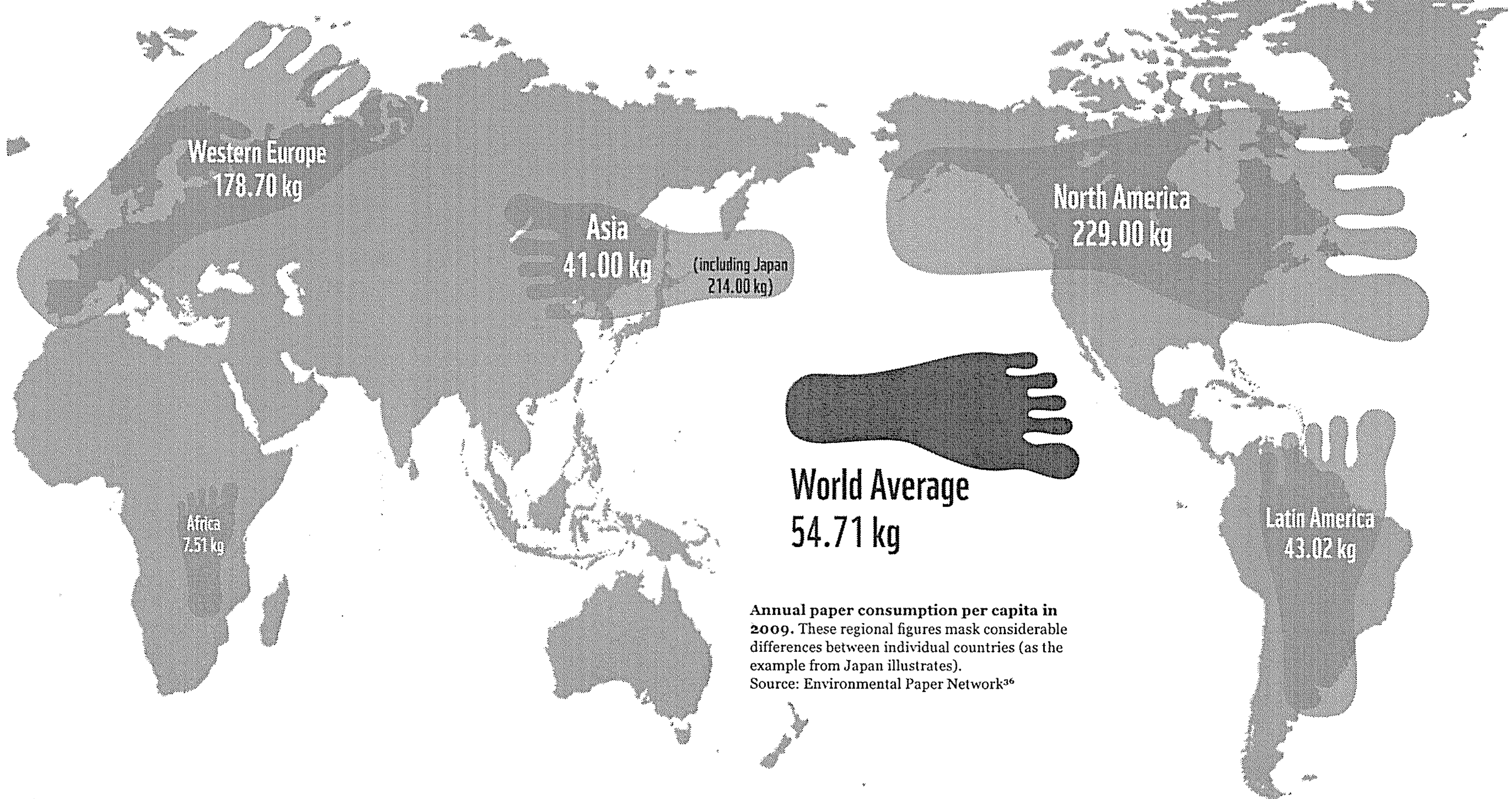
PAPER CONSUMPTION PATTERNS

Rich societies can reduce wasteful paper use, while the poor need more paper for education, hygiene and food safety.

Today, 10 per cent of the world's population consumes over 50 per cent of the paper[35]. This is hardly fair – paper is an important means to share knowledge and express ideas, improve sanitation and keep food safe.
A 10 per cent reduction in paper and paperboard consumption in North America and Europe would match one year's consumption in Africa and South America combined. Reducing wasteful consumption, like over-printing or over-packaging, would also ease the pressure on forests and land use, as paper use grows in developing countries.



Annual paper consumption per capita in 2009. These regional figures mask considerable differences between individual countries (as the example from Japan illustrates).
Source: Environmental Paper Network[36]

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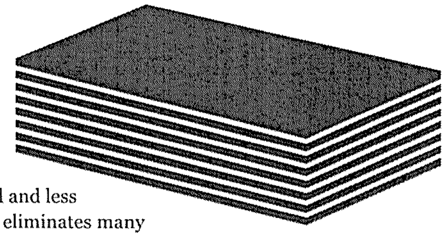
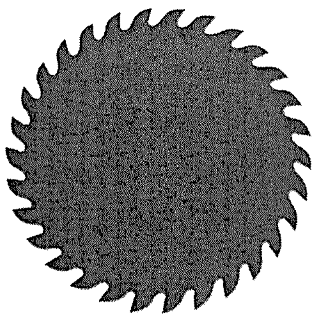
MORE PRODUCTS FROM LESS WOOD

In addition to increased recycling, more efficient processing and manufacturing can help reduce pressure to extract more wood from forests.



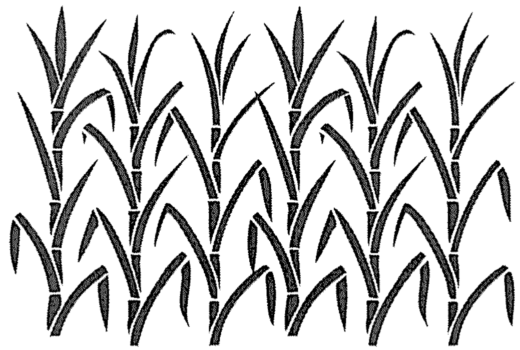
Changing technologies

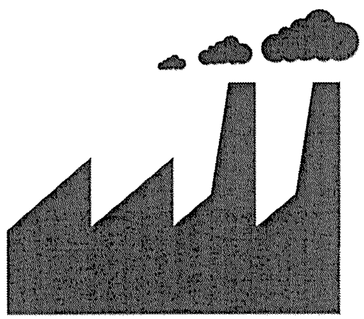
Engineered wood products make very efficient use of a given volume of wood and can be manufactured from fast-growing, underutilized and less expensive wood species. Engineered wood also eliminates many defects found naturally in wood, improving the material's inherent structural advantages. By-products from other production processes – small chips or unusable pieces of wood – can increasingly be used in composites and pulp. In the paper industry, new product designs and advances in engineering offer the prospect of near limitless reuse of short, recycled fibres.



Sawmills

On average sawmills operate at around 50 per cent efficiency[37]: in other words, only half the saw log is converted to sawn wood. In Europe and North America some mills reach above 70 per cent efficiency. Many mills are able to send their sawdust and off-cuts for further processing, such as the manufacture of panel products, but this is not always the case. While challenges vary regionally (tropical sawmills, for example, deal with a larger variety of log sizes and species), greater efficiency is possible through better logging and log grading systems, infrastructure and sawing technology. A 10 per cent increase in milling efficiency for tropical sawn wood could reduce global demand for saw logs by 100-200 million m^3 per year[38]. Increased efficiencies in small sawmills will increase profitability, benefiting local communities.





Pulp and paper mills

Ongoing innovation is enabling more efficiency in pulp and paper mills. New processing technologies mean more cellulose fibres can be extracted from a given volume of wood and less left to be burned. Smart use of mineral additives in paper, and better-engineered packaging (thinner but stronger), allow more units to be produced from the same volume of pulp. Increasingly mills can be seen as "bio-refineries" with by-products used to substitute oil from fossil fuels in materials such as polylactic acid.

Use of non-wood fibre

Other plant-based materials can supplement the use of wood fibre in many product lines: these include paper made from bamboo fibre or residues from food crops and furniture made from rattan. The relative efficiency and environmental impact of these other plant fibres will vary with the circumstances in which they are grown, sourced and processed and the fibre properties they bring to the end product.

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