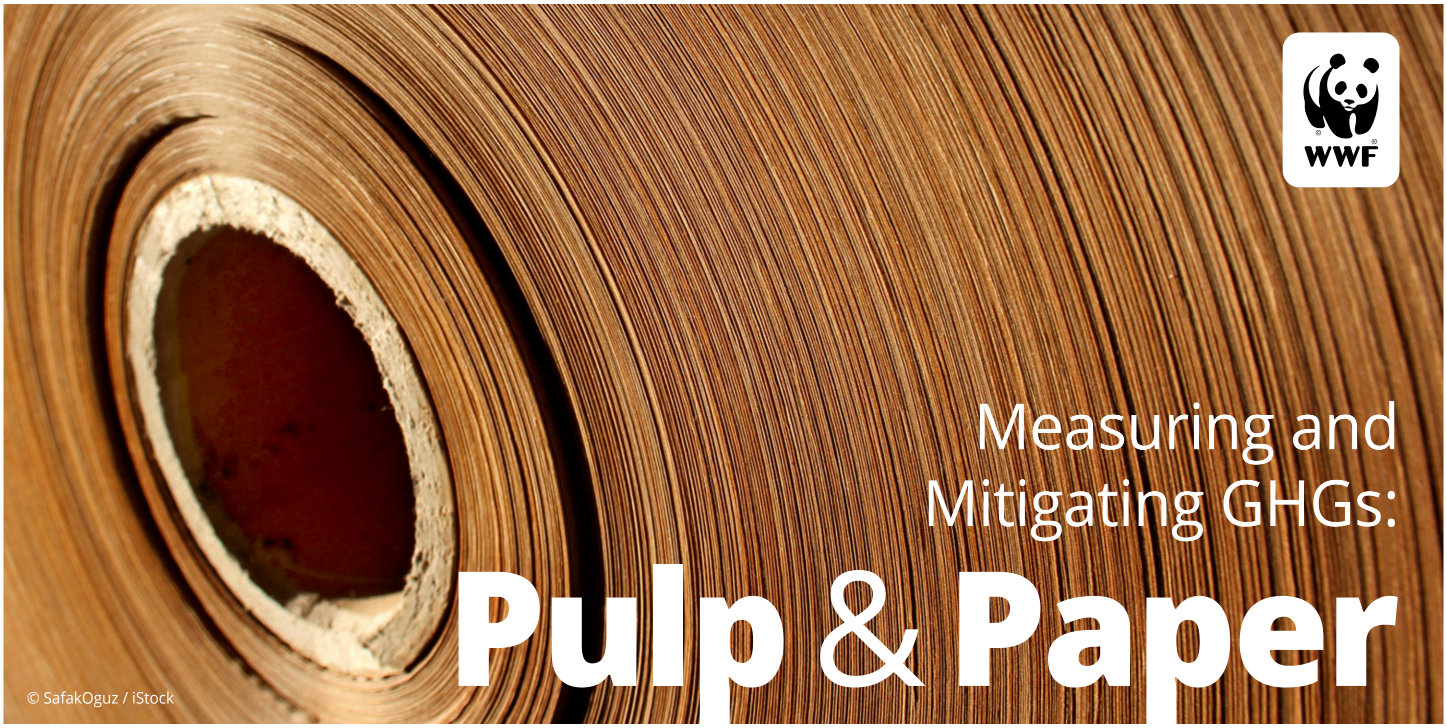

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Measuring and Mitigating GHGs: Pulp & Paper

Authors: Daniella Vallejo[1], Paige Vincent, Emily Moberg

There are millions of farms globally, each using a unique set of practices to cultivate their products in the local climate and soils. Thus, for any commodity, there are many thousands of different production systems and many thousands of different sources of greenhouse gases. The relative GHG emissions of producing the same product may differ drastically depending on how and where it is grown. To fully understand how to mitigate emissions and on which farms to focus mitigation efforts, we need a better grasp of the variations and gaps in data.

The authors do not think all the information to quantify GHG emissions from the paper value chain exists. At the very least, not in one place; this document is our attempt to collate currently available information. This is a working draft; debate, discussion, and comments are welcomed to advance the understanding of this topic. WWF will be producing similar pieces on other key food commodities to stimulate similar discussions. All comments should be justified with evidence and data and sent to Emily Moberg at GHGCommodities@wwfus.org.

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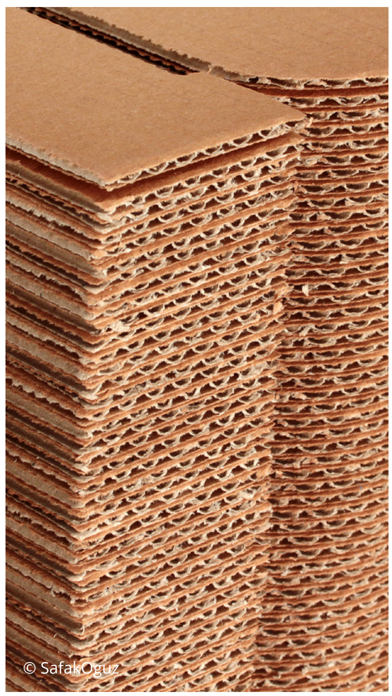
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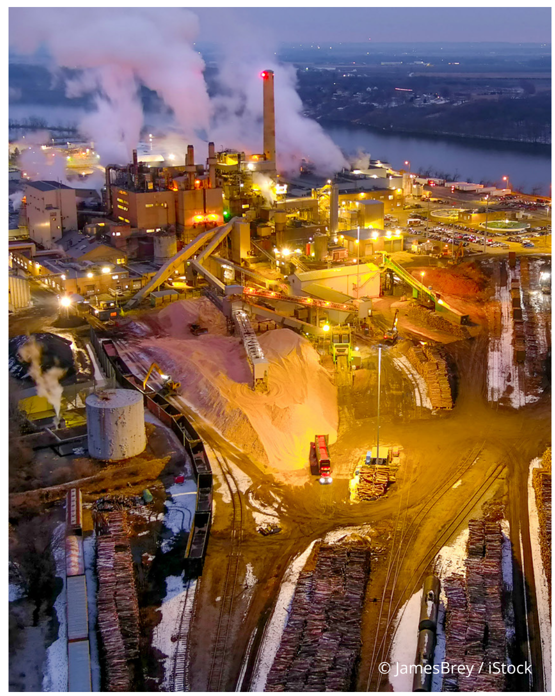
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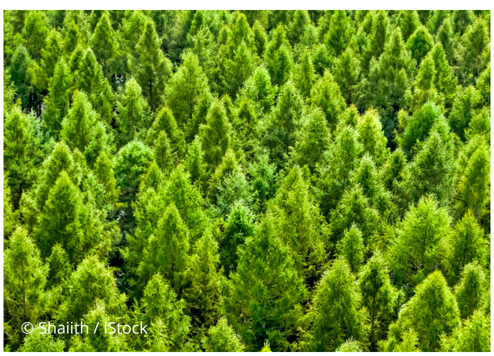
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ABOUT PULP & PAPER

Paper is a ubiquitous part of life – for documents, books, packaging food, and wiping up after spills. The FAO estimates that a total of 1.7 billion cubic meters of industrial roundwood (excludes fuel wood) are produced each year. Of this, about 30% is pulpwood.[2] This is used to make 17 million tonnes of pulp. This pulp, plus pulp from recycled paper and non-wood pulp is then used to make 41 million tonnes of paper and paperboard. About half that paper is recovered each year.

Paper consumption tends to increase with GDP, so increased consumption is expected.

PULP & PAPER SUPPLY CHAINS

Trees are grown in timberlands ranging from natural forests to plantations. Wood may be harvested through thinning (prior to a major harvest at the end of a rotation), or during a harvest at the end of a rotation. This final harvest may remove all trees (clear-cut) or a small percentage.

The logs are then taken to a mill, typically in the same region. Plantations are often closer to mills than are other timberlands. Pulpwood is milled either in a pulp mill or an integrated mill that also produces the paper product. When pulp is milled to be sold, it is dried and then shipped with low water content; this pulp may be sold across the world to make paper products.

Different pulps are typically mixed to make papers. There are many types of paper ranging from newsprint, to high-quality bleached printing paper, to bathroom tissues, to cardboard. The type of pulp and manufacturing differ to produce paper that is functional for its intended use. These paper products are consumed around the world.

The largest consumers of paper products are China (28%), the rest of Asia (22%), Europe (22%), and North America (18%). South America consumes about 4% and Africa about 3%.[3] The local recycling and material-solid waste disposal practices then determine the end-of-life for those consumed products.

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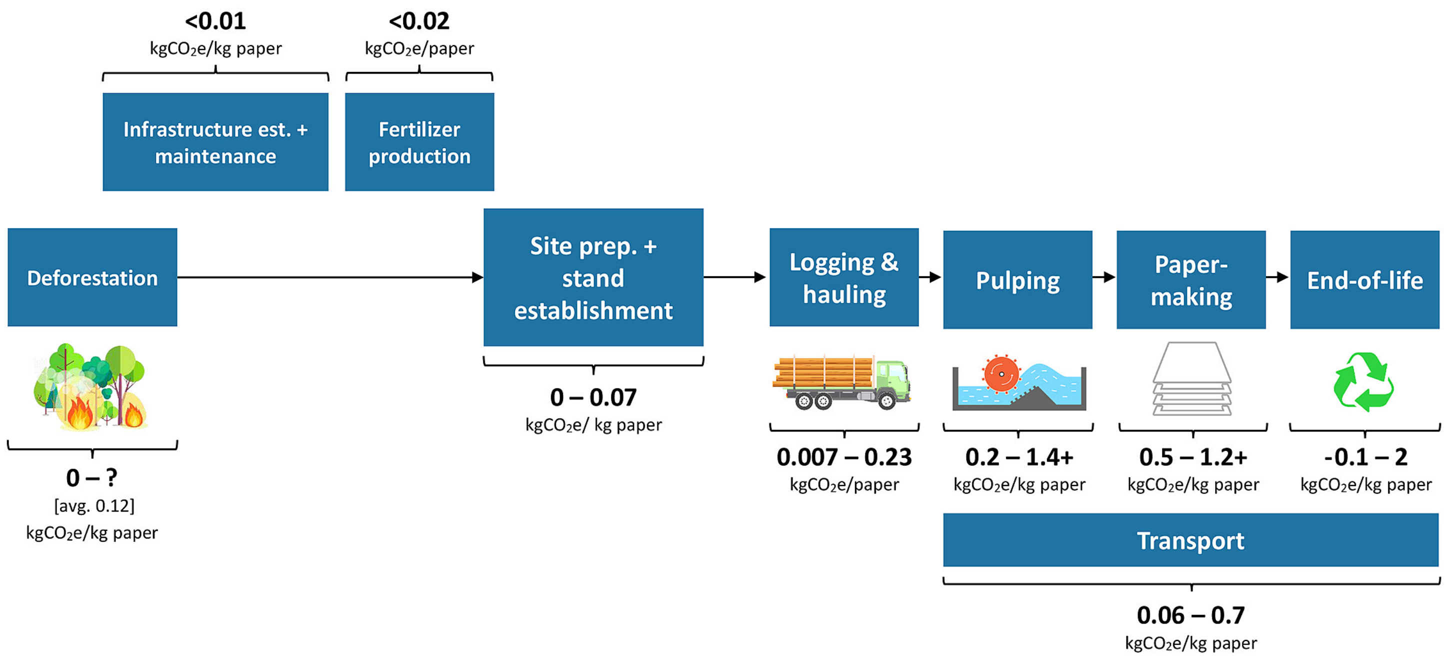
GHG EMISSIONS FROM PULP & PAPER SUPPLY CHAINS

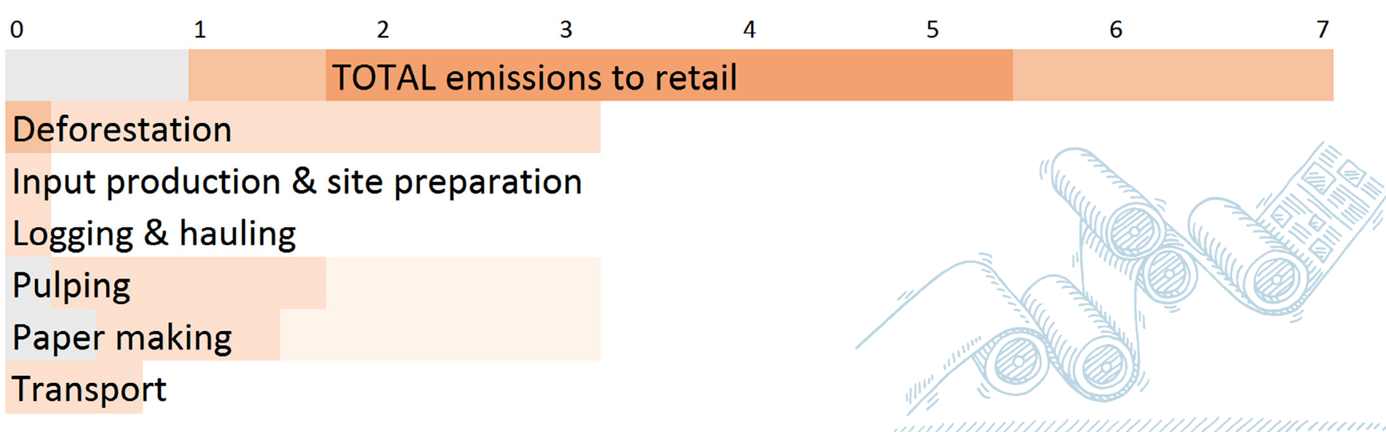
Excluding biogenic emissions from forestry, the GHG footprint of paper to factory gate ranges from about 1[4] to 7[5] tCO_2e/t paper; values between 2 and 5.5 seem typical. End-of-life can either offset or add to emissions (-0.1 – 2 tCO_2e/t paper). The figure below summarizes these ranges. Note that this excludes forest carbon stocks other than deforestation.

Figure 1: Range of GHG emissions from pulp and paper supply chains



The full range of impacts (in $kgCO_2e$/kg paper) is shown below, with the typical range highlighted in darker orange. Note that due to lack of data on typical practices, many of these processes have only the full range.

Because natural and plantation forests represent a huge carbon stock and different management practices can influence the size of that stock over time, how accounting occurs for that stock is particularly critical. This remains unsettled. A few details about the implications of accounting decisions for timber are explained in the next section.



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GHG ACCOUNTING FOR TIMBER

Functional Units

The functional unit for timber product varies at different stages of its life cycle and depending on what the final intended product is.

Most industrial wood is measured in cubic meters (m^3) of underbark until the mill gate. The functional units for sawn wood often reflect the end use; e.g., one wooden house frame for a typical home in the region of study. For pulp and paper, the most common functional unit is one tonne of the final product. However, when that paper is used for packaging, (such as pallets and wooden crates) the functional units typically reflect the amount of product and distance over which they function (i.e., tonne-km). Here we have worked to normalize units to kilogram of paper for clarity.

Allocation

Allocation: Consider two sources of virgin paper pulp: trees intended primarily for pulpwood and pulpwood that is a byproduct of other timber production. For the latter, allocation is important because the economic value of logs is higher than of tops and branches used for fuel or pulp. For mature trees being harvested for logs, around 70%–80% of the volume of the tree is roundwood (not branches/tops).[6]

Many timberlands are also thinned before the end of the rotation to reduce competition among the trees (so remaining trees grow more quickly); these smaller trees likely go towards pulp or pellets, but inputs to the whole timberland (e.g., fertilizer or biomass sequestration) need to be allocated across the thinned and final products. The differences between mass and economic allocation are large in this case.[7] Most studies do not account for carbon emissions or sequestration from the forest, so allocation does not occur; this is an important issue if these emissions are considered.

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System expansion: System expansion is a method for avoiding allocation in which the boundaries of the system are expanded to consider a product that the system-of-interest is displacing. Rather than allocating emissions between byproducts, the emissions from the displaced product are subtracted. System expansion is commonly used in life-cycle assessments for paper: for displaced fossil fuel use for heat or electricity when byproducts or end-products are burned and for paper products' displacement of plastic alternatives. Note that the process of choosing the displaced product can lead to cherry-picking alternatives, but this technique is appropriate when reflective of true system-level changes.

This likely merits more attention. Global solutions for climate often include the replacement of wood as a substitute for cement and steel, which could mitigate between 0.25 and 1 $GtCO_2e$/yr.[8]

Carbon Stocks

There are massive fluxes of greenhouse gases from forests that produce paper and pulp. Which proportions of those fluxes should be attributed to paper is unsettled, and forthcoming guidance from the GHG Protocol is expected to clarify this. In the next paragraphs, we have summarized the magnitude of key fluxes (details on calculations in later sections). Note that because accounting credit typically is given for changes in stocks, the fluxes for emissions that could be prevented or sequestered are what is relevant.

- **Deforestation for pulpwood plantations:** Average 0.12 tCO_2e/t paper.[9] This estimate is only for gross loss of carbon. Over the past 20 years all plantations (not just those for timber), were a net sink of CO_2; plantations in temperate and subtropical regions outweighed the net source in tropical plantations (about 40% larger sink).[10] It is unclear how much of this is from timber plantations.

- **Degraded forests:** Better forest management, whether by preventing early harvesting or promoting practices that sequester carbon, has the potential to reduce emissions by approximately 0.42 – 0.8 tCO_2e/t paper. Improved plantation management has mitigation potential of about 0.1 tCO_2e/t paper.

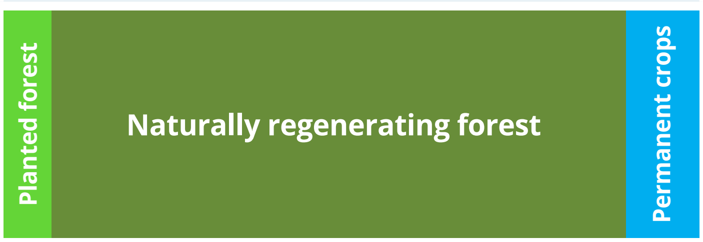
Many analyses of pulp and paper manufacture ignore the cycling of greenhouse gases within the forest biomass. They assume that if the forest is sustainably managed, the biomass removed by harvest is matched by new tree growth so no *net* change occurs.[11] This assumption is likely untrue in many circumstances; deforestation occurs to plant pulp and paper plantations and unsustainable, illegal timber harvest is a major problem; on the other hand, proactive forest management can potentially increase carbon drawdown.

Tree-cover loss can come from responsible forestry, permanent or temporary deforestation, or wildfire. 26% of tree-cover loss from 2001–2015 came from forestry; 27% (total) from deforestation (24% and 23% from shifting agriculture and wildfire respectively).[12]

Figure 1: Approximate extent of forest areas

Global Forest Distribution

The definition of a forest can be murky. Globally, the FAO categorizes 4070 million ha of land as forest; of this 93% is naturally regenerating and 7% is planted forest.[13] About half of this area undergoes some type of timber production.[14] In addition, 168 Mha are under permanent crops, which include trees for fruit (~54 Mha), rubber (~12 Mha), cocoa and coffee (~23 Mha), oil palm (~28 Mha), and tree nuts (~14 Mha) but appear to exclude plantations for wood fiber. Many studies of carbon fluxes group forest plantations, which may include some of these perennial crops. About 260 Mha are forest plantations.[15]



The following practices have GHG implications:

- **Deforestation:** Forests are cut down to make way for pulpwood plantations. World Resources Institute (WRI) estimates that between 2001 and 2015, 1.8 Mha of forest were lost for pulp and paper production.[16] This deforestation is largely concentrated in Indonesia, although some occurs in Brazil, China, and Malaysia as well. Averaged across all paper production, deforestation adds 0.12 tCO_2e/t paper.[17] Note that permanent deforestation for other cropland is extensive, and that timber from the removed forests may often be sold.

Timber plantations also have significant stocks of carbon biomass, although typically much lower than a mature forest (~30–60tC/ha at half-rotation time), so while this may "net" out some emissions, it is unlikely to do so by more than about 30%.[18]

- **Sub-optimal harvest practices:** Many forests have pre-mature entry for harvest; this is when harvest occurs before the rotation period completes. This can result in the degradation of forest growth. Estimates suggest that 1–1.8 $GtCO_2e$/yr of GHG emissions could be avoided by preventing early

forest re-entry. If 16% of this forestry went to pulp and paper, divided across all paper produced this adds 0.4 – 0.7 tCO_2e/t paper.[19]

Large-scale logging drives deforestation in Myanmar, the Amazon in Brazil and Peru, Cameroon, Zambia, Angola, Madagascar, and Eastern Australia.[20]

- **Carbon-promoting forestry management:** Trees naturally compete for nutrients and sunlight. Thus, thinning forests by removing some trees can promote faster growth rates for the remaining trees by limiting this competition. Changing the rotation length can also significantly alter carbon fluxes, as there is a larger "average" amount of carbon stored in the forest over time. For natural forests, globally better management is estimated to have 0.44 – 1.48 $GtCO_2e$/yr mitigation potential; 21% of these forests are used for timber and globally ~16% of wood is used for pulp and paper, which results in about 0.02 – 0.12 tCO_2e/t paper potential. Improved plantation management has a global potential of about 0.28 – 0.45 $GtCO_2e$/yr. From Griscom's supplemental data and FAO-STAT data on permanent crops, about 35% of this is likely timber plantations and we assume that 30% of this goes to pulp and paper (none to fuelwood) resulting in 0.07 – 0.12 tCO_2e/t paper.[21]

- **Carbon embedded in products:** Some analyses have noted that the carbon in wood products themselves is significant. While for long-lived products like furniture and buildings this may represent long-term storage, for paper products, it does not. Tracking carbon within products as part of accounting for mass flows and end-of-life is, however, reasonable.

Currently, the emissions from negative or positive practices are not typically accounted for (although a few companies have proposed methodologies for this accounting). In general, drawdown from forest management does not offset the emissions from making paper even with responsible sourcing meeting or exceeding standards like those of the Forestry Stewardship Council, which should ensure that emissions from illegal harvest (often re-entry), lack of a management plan, and failure to maintain high conservation value forests do not occur.[22]

Stands of trees store huge amounts of carbon. Changes in these stocks likely represent up to 3 $kgCO_2e$/kg paper in areas where de-forestation occurs and about 0.1 – 0.6 $kgCO_2e$/kg paper on average. The magnitude of improved practices per kg of paper is likely near this lower end (0.1 $kgCO_2e$/kg paper).

Logging

The fuel used for machinery operation to remove timber from the forest also releases GHGs. Typical emissions across all non-biogenic forestry practices are small (<0.1 kgCO_2e/kg paper but range from 0.007 to 0.23[23]) and most come from harvest. Infrastructure typically has a negligible contribution.

Emissions from the logging process itself are small, but when logging occurs greatly affects the overall emissions and stand health.

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Pulping

Pulping contributes between **<0 and 1.4 tCO_2e/t paper**. These differences arise from the energy mix used for production and whether pulp is made from wood or recycled paper. The upper end of this range may be higher (Table 1), as total emissions from pulping and papermaking together are often three to six times higher and pulping often contributes about half the emissions between these two processes. Because biomass from chemical pulping is burned for energy, pulping is sometimes considered carbon neutral or negative.[24] Emissions from re-pulping recycled paper were also within this range.[25]

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Pulping is the process by which the solid mass of the tree is reduced to fibrous strands that can be used to make paper. There are multiple methods for pulping ranging from mechanical to chemical (or combinations of the two). These methods have different yields of pulp (per mass of wood) and composition (e.g., of cellulose); the yield ranges from over 90% for mechanical pulping to under 50% for chemical pulping.[26] Mechanical pulp tends to be used for newsprint, while chemical pulp is used for other papers.

Pulping is energy-intensive, so GHG emissions in the pulping stage come largely from electricity use, although emissions from the processing chemicals may also be significant. Often, analyses use system expansion to count the burning of biomass (bark and black liquor) as replacing the relevant energy mix without biomass; the use of biomass essentially subtracts emissions from the electricity use.

- **Chemicals:** Emissions from chemicals used in pulp and papermaking ranged from **0.02**[27] **to 0.28**[28] **tCO_2e/t paper**; the low-middle range seems more typical (0.04 – 0.14 tCO_2e/t paper).[29]

Table 1: GHG Emissions from pulping & paper-making processes

GHG emissions from virgin pulping	
Product	**GHG emissions** (tCO_2e/t paper)[30]
Paper towel[31]	-1
Eucalyptus pulp[33]	1.4
Tissue paper[35]	0.61
Air-dried pulp[37]	0.7
Paper[39]	0.16

GHG emissions from papermaking	
Product	**GHG emissions** (tCO_2e/t paper)
Paper towel[41]	1 – 1.17
Cardboard box[42]	1.08
Printing paper[43]	0.47
Writing paper[44]	0.98
Tissue paper, virgin pulp[45]	0.48
Tissue paper, recycled paper ^	1.05
Paper towel[47]	1 – 1.17

GHG emissions from pulping + papermaking	
Product	**GHG emissions** (tCO_2e/t paper)
Cardboard box[32]	2.7
Cardboard box[34]	3.0
Cardboard box[36]	0.79 – 1.02
Cardboard box[38]	1.16
Newsprint[40, *]	2.9 – 5.9
Uncoated printing paper*	3.5 – 6.3
Tissue paper*	6.6 – 7.7
White board*	2.1– 6
Boxboard*	2.1 – 5.1
Corrugated medium*	2
Coated printing paper*	3.5 – 6.7
Wrapping paper*	2.5 – 6.3
Paper and paperboard from recycled paper[46]	0.99
Offset paper[48]	0.96
Newsprint[49]	0.21 – 0.51
SC paper[50]	0.36 – 0.63

Papermaking

Paper is often made from different pulp sources both to achieve desired properties and for cost. Here was assume that 1.1 kg pulp is used per kg of paper.[51] Similar to pulping, papermaking is energy intensive. The energy mix, type of paper being made, and type of pulp used largely determine emissions from this stage.

Between **0.47 and 1.17 tCO_2e/t paper** were attributed to the paper-making stage, although as Table 1 highlights, the emissions from both pulp and papermaking (when not disaggregated) may be much higher, suggesting the contribution of paper (which is often roughly half of the total) may also be higher.

The emissions from pulping and papermaking are high and tend to dominate the footprint of paper. While there is variation across types of paper, what processes are used, and what the electricity mix of the location is, these emissions can range from about **0.2 to over 7 $kgCO_2e$/kg paper.**


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Transport

Transport of pulp to the paper factory, of paper to the consumer, and waste products to end-of-life treatment were accounted for in various studies. The emissions from transport ranged from **0.06 to 0.7 tCO_2e/t paper**[52]. Given the differences in cumulative distances and modes of transit, contributions from transport were evenly distributed throughout this range.[53] High-end emissions resulted when pulp was transported across continents.

End-of-Life

The final destination of the paper product greatly impacts overall GHG emissions – not because of transport but because of differences in end-of-life. Paper can be recycled, landfilled, or incinerated. The relative proportion of paper going through each process depends on the type of paper product and location. In general, cardboard is recycled at a higher rate than other papers. Often end-of-life is taken as a weighted average across practices used in a location; the total emissions can be negative when system expansion is used to account for incineration displacing other electricity (typically around -0.1 tCO_2e/t paper) up to about 2 tCO_2e/t paper.[54]

- Landfilling produces high emissions because of methane production. Estimates ranged from 0.05 to 0.33 tCO_2e/t paper.[55]

- Recycling involves re-pulping the paper and heating it to remove contaminants like wax. It is then screened, cleaned, and dried. The water from this process also must be cleaned.[56] The energy taken to re-pulp is discussed in “pulping”. Some analyses subtracted emissions from recycled paper to account for the avoided production of new pulp.

- Incineration of paper is a relatively low-GHG intensity method of disposal, since the embodied carbon in the product is assumed to be short lived. When energy recovery is part of the incineration, credits from displaced alternative fuels may be generated; these resulted in -0.06 and -0.13 tCO_2e/t paper in the few studies that investigated this.[57]

How common these practices are varies widely; Table 2 shows variation across three locations for recycling.

Table 2: Recycling rates for several top-consuming geographies

	Corrugated boxes	Other packaging	Non-newspaper non-durable goods	Total
US[58]	96%	20.8%	43.1%	68.2%
EU[59]	84.2%			72%[60]
China[61]				49%


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OUTLIER EMISSIONS SOURCES

The variability in emissions per kg of paper highlights the large mitigation potential that exists across current practices. Here we highlight the “low hanging fruit” or practices that drive unusually high emissions intensity. These practices may be good targets for initial screening for improvement.

- **Prevent deforestation and early entry:** The footprint from deforestation is large, and deforestation of forests for pulp plantations continues. Early entry for harvest also greatly reduces the carbon sequestration in forests.
- **Increase renewable energy use for pulping and paper making:** The pulping and paper processes are energy intensive; greater use of renewables and responsible biomass can dramatically decrease the footprints from these processes.
- **Increase beneficial end-of-life and reuse**

PRODUCTION SYSTEMS

For timber, the key differentiators for wood production are among forest types (tropical, temperate, and boreal) and in the intensity of production. For pulp and paper products, some woods are destined for pulp, while wood for pulp and paper may also come from thinnings and smaller parts of trees used for saw boards, etc.

Broadly, the local climate influences both which trees grow in an area and how quickly they grow. Different trees have different properties that make them suitable for different end-products, and the differing growth rates influence the amount of wood produced. Local site factors (soil quality, slope, etc.) are equally important in determining growth.

Most forest land is boreal and tropical, while most tree plantations are tropical or subtropical. Table 3 summarizes the forest area and GHG fluxes from the growth of these forests. Note that plantation area includes plantations like oil palm and other food crops.

Table 3: Forest area and carbon fluxes from Harris et al. (2021)[62]

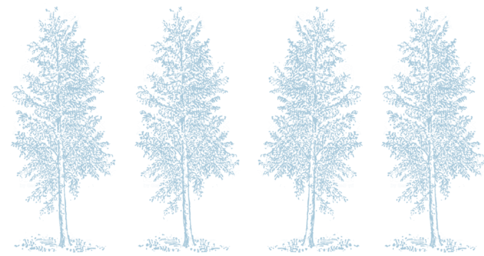
	Forest area in 2000 (Mha)	Plantation area in 2000 (Mha)	Net GHG flux ($GtCO_2e/yr$)	Net GHG flux plantation only ($GtCO_2e/yr$)	Removal rate AGB & BGB ($MgCO_2e/ha$) [Plantation]
Boreal	1090	0.21	-1.6	-0.0027	2.44 [13.2]
Temperate	590	12	-3.6	-0.073	7.87 [14.0]
Subtropical	340	54	-0.65	-0.31	5.73 [16.6]
Tropical	1990	47	-1.7	0.16	3.9 [21.0]

How intensively timberland is managed is another key property of the system:

- Natural systems have natural regeneration and no site preparation, stand establishment, or maintenance.[63]
- Extensive systems use artificial regeneration through simple methods such as seed sowing, no fertilization, and otherwise minimal initial site clearing and pruning.
- Intensive systems use artificial regeneration through seedling cultivation and planting, and fertilizer application for site preparation and stand maintenance. Within this, plantations are often considered separately.

In each system, the rotation length is a critical factor; how quickly the trees grow and what prices are offered determine the economically optimal length. Thinning the trees prior to the final harvest is often done to prevent slower growth due to competition.

Transforming pulpwood into pulp and paper is also a GHG-intensive process. Both the type of pulp and type of paper matter for GHG emissions, as shown in Table 1.



REGIONS

The footprint of pulp and paper differs regionally, but different stages of production occur in different regions. The biogenic footprint from forest management and deforestation & from pulping depend on the region of origin. The footprint of paper production depends on the region of paper manufacture, which may or may not be the same as the region of origin. The footprint from end-of-life depends on the region where the paper is used.

For end-of-life emissions, the local recycling rate and whether there is electricity co-generation from waste incineration are the major determinants of GHG emissions.

Table 4 (below) shows some statistics on pulp production in leading production countries.

Emissions from paper are a focus for China, in particular, because they consistute about 10% of China's industrial GHG emissions.[70]

Table 4: Pulp and forest statistics for selected countries

	Wood pulp production (million tonnes/yr)[64]	GHG intensity ($kgCO_2e$/kg pulp)[65]	Deforestation for plantations (ha)[66]	Planted forest (Mha)[67]	Naturally regenerating forest[68]	Paper production[69]
USA	51	~0.4 – 0.5	?	28	282	70
Brazil	21	?	1.3k	11	487	10
Congo	?	?	?	0.06	127	?
Indonesia	8	?	109.5k	5	88	12
Sweden	12	~0.3	?	14	14	10
China	14	~1.4+	4.8k	84	135	113

MITIGATION

There are two main areas of intervention: forests and manufacturing energy.

For interventions in forests, the current harvesting status is critical.

Prevent deforestation: If the forest is a primary, unharvested forest, preventing permanent deforestation from logging or habitat conversion for agriculture (often preceded by logging) is critical.

Reduced-impact logging and timberland management for carbon: If the forest has some legal harvest, ensuring that the rotation period is sustainable and followed is important. The issue of early re-entry is prominent in tropical forests, but timberlands in other regions could also potentially sequester more carbon if management changes occurred (like longer rotation lengths). Whether this comes out in an accounting framework as mitigation or sequestration depends on the baseline set.

Producing paper requires large amounts of energy; paper manufacturing constitutes a significant portion of energy use in many countries, including China (currently the largest global GHG emitter). Increased efficiency and a shift towards renewable energy can dramatically reduce these emissions. Note that not all energy use in paper manufacturing is electricity, which currently limits how much a cleaner grid contributes to paper's footprint.

Table 5: Mitigation potential summary

Mitigation Potential Table				
Intervention	Target	Cost	Mitigation potential	Barriers
Prevent deforestation for plantations	Tropical forests; governments		4.4 $MtCO_2e$/yr (based on current deforestation rates)	
Reduced impact logging[71]	Governments, buyers	\$0.6 - \$1.8/tCO_2e	1 – 1.8 $GtCO_2e$/yr	Monitoring
Renewable energy for pulp & paper-making electricity use		?	?	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TOOLS & DATA AVAILABILITY

The GHG footprint of paper is fragmented in the literature, and accounting is unsettled. The GHG Protocol has a pulp and paper and a wood tool available (https://ghgprotocol.org/calculation-tools#sector_specific_tools_id) and several corporations have their own in-house tools. Forthcoming guidance from the GHG Protocol on accounting in this sector in late 2022 / early 2023 is expected to clarify many of the accounting decisions discussed here.

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Change at the speed of life

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CITATIONS / FOOTNOTES

1 Daniella compiled the dataset of life-cycle assessments for timber that formed the basis of this work. The dataset can be found at agimpacts.mit.edu.

2 Food and Agriculture Organization (FAO).

3 Data on paper and paperboard (production + imports – exports) averaged from 2018-2020. Food and Agriculture Organization (FAO), "FAOSTAT," n.d.

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10 Harris et al., "Global Maps of Twenty-First Century Forest Carbon Fluxes."

11 E.g. "We assume that biogenic carbon emissions are balanced by the carbon fixed by the trees, given that the pulp comes from sustainably grown forests." Gemechu et al., "A Comparison of the GHG Emissions Caused by Manufacturing Tissue Paper from Virgin Pulp or Recycled Waste Paper."

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