Verifying Greenhouse Gas Emissions

Methods to Support International Climate Agreements

Trust in international agreements to limit future greenhouse gas emissions will depend on the ability of each nation to make accurate estimates of its own emissions, monitor their changes over time, and verify one another's estimates with independent information. Countries have the capability to estimate their carbon dioxide emissions from fossil-fuel use with sufficient accuracy to support monitoring of an international treaty, but accurate methods are not universally applied and the estimates cannot now be checked against independent data. Deployment of existing methods and technologies could, within five years, yield a capability to both estimate and verify carbon dioxide emissions from fossil-fuel use and deforestation—which comprise approximately three-quarters of greenhouse emissions likely covered by a treaty.

Agreements to limit future emissions of greenhouse gases are the focus of international negotiations, and with such accords will come the need to accurately estimate emissions and monitor their changes over time. In this context, the National Research Council convened a committee of experts to assess current capabilities for estimating and verifying greenhouse gas emissions and identify ways to improve these capabilities.

The committee focused on human-made emissions of six greenhouse gases that have long lifetimes in the atmosphere and therefore will affect global climate for decades or even millennia to come: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorinated hydrocarbons (PFCs), and sulfur hexafluoride (SF_6)—all of which are covered by the United Nations Framework Convention on Climate Change (UNFCCC)—and chlorofluorocarbons (CFCs), which are covered by the Montreal Protocol. Particular focus was given to CO_2 because this greenhouse gas is the largest single contributor to global climate changes. Only data in the public domain were considered because public access and transparency are necessary to build trust in a climate treaty.

The committee examined three categories of methods for estimating greenhouse gas emissions: national inventories, atmospheric and oceanic measurements and models, and land-use measurements and models (Box 1). The first method is used by countries to estimate and report their emissions to the international community under the United Nations Framework Convention on Climate Change (UNFCCC); the second and third are research methods that could help verify self-reported estimates. The committee found that deploying existing methods and technologies could, within five years, yield a capability to estimate and verify carbon dioxide emissions from fossil-use and deforestation. As these types of emissions comprise about three-quarters of the greenhouse emissions likely to be covered by a treaty, these improved capabilities could provide useful support to international negotiations.

Current methods produce emissions estimates with unacceptably high uncertainties; in some cases the uncertainties are larger than the expected emissions reductions over a treaty's lifetime (Table 1). However, it may not be necessary to accurately measure all greenhouse gases to support treaty monitoring and verification. Approximately 90 percent of global emissions covered by the UNFCCC are from energy and agriculture, forestry, and other land use, making these activities an obvious focus for monitoring. The majority of emissions are in the form of CO_2 from fossil-fuel use (Figure 1), which can be estimated accurately.

Recommendations

Strategic investments focused on the most important sources of greenhouse gases in each country and the highest emitting countries (Figure 2), could yield an improved ability to monitor and verify an international climate agreement within five years. The required investments are in three categories: strengthening national greenhouse gas inventories, improving independent estimates of fossil-fuel CO_2 emissions, and improving independent estimates of fluxes from land use.

Strengthening National Greenhouse Gas Inventories

The UNFCCC framework will likely form the basis for a future climate agreement because it has broad international support and offers established mechanisms for preparing national inventories of emissions and incorporating new information and methods. However, the framework also has several shortcomings. For example, developing countries do not measure or report their emissions regularly, even though rapidly industrializing countries are among the world's highest emitters of greenhouse gases. Under the UNFCCC, developed countries produce detailed annual estimates of sources and sinks of six greenhouse gases using complex methods and country-specific data on emissions generating activities, and the resulting national inventories are subject to international review of methods and data sources. If applied, these rigorous methods allow countries to estimate CO_2 emissions from

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Box 1. *Current Methods for Estimating Greenhouse Gas Emissions*

UNFCCC national inventories
Countries calculate emissions by multiplying levels of greenhouse gas-emitting activities—such as energy production and use; industrial processes and product use; agriculture, forestry, and other land use; and waste—by the corresponding rate of emission per unit of activity.

Atmospheric and oceanic measurements (tracer-transport inversion)
Emissions of total human-made and natural sources and sinks of greenhouse gases are estimated using atmospheric and oceanic measurements of greenhouse gases and models of air and water flow.
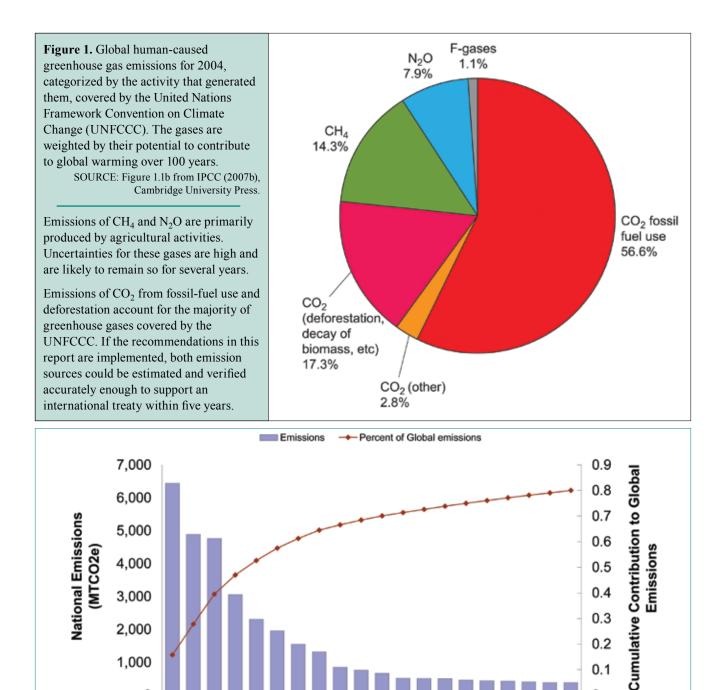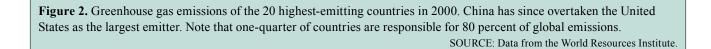
Land-use measurements and models
Satellite information on land-surface characteristics and change is converted into CO_2, CH_4 and N_2O emissions estimates using biogeochemical models constrained by measurements of greenhouse gas exchange between the land and the atmosphere.

Figure 1. Global human-caused greenhouse gas emissions for 2004, categorized by the activity that generated them, covered by the United Nations Framework Convention on Climate Change (UNFCCC). The gases are weighted by their potential to contribute to global warming over 100 years.

Emissions of CH_4 and N_2O are primarily produced by agricultural activities. Uncertainties for these gases are high and are likely to remain so for several years.

Emissions of CO_2 from fossil-fuel use and deforestation account for the majority of greenhouse gases covered by the UNFCCC. If the recommendations in this report are implemented, both emission sources could be estimated and verified accurately enough to support an international treaty within five years.

N₂O: N_2O 7.9%
F-gases 1.1%
CH₄: CH_4 14.3%
CO₂ fossil fuel use: CO_2 fossil fuel use 56.6%
CO₂ (deforestation, decay of biomass, etc): CO_2 (deforestation, decay of biomass, etc) 17.3%
CO₂ (other): CO_2 (other) 2.8%

Legend: ▬ Emissions   ◆ Percent of Global emissions

Left axis: National Emissions (MTCO2e) — 0 to 7,000
Right axis: Cumulative Contribution to Global Emissions — 0 to 0.9

Countries (x-axis): United States of America, European Union, China, Indonesia, Brazil, Russian Federation, India, Japan, Malaysia, Canada, Mexico, Myanmar, Korea (South), Australia, Ukraine, Nigeria, Iran, Congo, Dem. Republic, South Africa, Venezuela

Country

Figure 2. Greenhouse gas emissions of the 20 highest-emitting countries in 2000. China has since overtaken the United States as the largest emitter. Note that one-quarter of countries are responsible for 80 percent of global emissions.

Table 1. Uncertainties in Methods for Estimating Annual, National Greenhouse Gas Emissions

Gas	Source	Method	Current Uncertainty	Uncertainty of Improved Methods
CO$_2$	Total anthropogenic	UNFCCC inventory	<10% *developed countries*	<10% *all countries*
	Fossil-fuel combustion	UNFCCC inventory	<10% – 25% *developed countries*	<10% *all countries*
	Fossil-fuel combustion	Atmospheric measurements and models	50% – >100%	<10% – 50% *annual* <10% – 25% *decadal change*
	Large local sources (e.g., cities, power plants)	Atmospheric measurements and models	>100%	10%-25% *annual* <10% *decadal change*
	Agriculture, forestry, and other land use (AFOLU) net emissions	UNFCCC inventory	<10% – 100% *developed countries*	<10% – 50% *all countries*
	AFOLU	Atmospheric measurements and models	>100%	50% – >100%
	AFOLU	Land-use measurements and models	10% – 100%	10% – 50%
	Deforestation and degradation source, afforestation sink	Land-use measurements and models	10% – 100% *forest area change* 25% – 100% *emissions*	<10% – 25% *forest area change* 10%-25% *emissions*
CH$_4$	Total anthropogenic	UNFCCC inventory	10% – 50% *developed countries*	<10% – 50% *all countries*
	Total anthropogenic	Atmospheric measurements and models	25% – >100%	10% – 50%
	Energy, industrial processes, and waste	UNFCCC inventory	<10% – >100% *developed countries*	<10% – 25%
	AFOLU	UNFCCC inventory	10% – 100% *developed countries*	10% – 50%
N$_2$O	Total anthropogenic	UNFCCC inventory	10% – >100% *developed countries*	10% – 100%
	Total anthropogenic	Atmospheric measurements and models	50% – >100%	25% – >100%
	Energy and industrial processes	UNFCCC inventory	25% – >100% *developed countries*	25% – 100%
	AFOLU	UNFCCC inventory	10% – >100% *developed countries*	10% – 100%
CFCs, PFCs, HFCs, and SF$_6$	Industrial processes	UNFCCC inventory	<10% – 100% *developed countries*	<10% – 50% *all countries*
	Industrial processes	Atmospheric measurements and models	50% – >100%	10% – >100%

NOTES: >100% means cannot be certain if it is a source or sink. Uncertainty levels correspond to 2 standard deviations.

Shaded rows are the self-reported values; unshaded rows are the independent checks on the self-reported values from independent methods.

Developed countries—based on 2006 data reported by 5 developed countries (Denmark, Greece, Portugal, the United States, and Poland) with a range of institutional capabilities for compiling inventories. In countries where AFOLU sources dominate energy and industrial sources, the uncertainties for total anthropogenic emissions would be much higher.
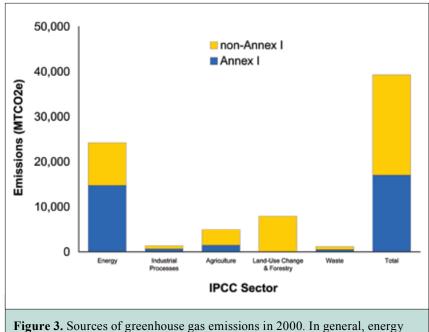
fossil-fuel use with uncertainties of less than 10 percent. In contrast, developing countries are required to make only periodic estimates of CO_2, CH_4, and N_2O, and the methods used to calculate emissions are simple, less accurate, rely only on global data, and are not reviewed. Financial and technical assistance will be required for developing countries to build the capacity to collect, analyze, and report emissions regularly.

- *UNFCCC parties should strengthen self-reported national emissions inventories by working toward:*
  - *extending regular, rigorous reporting and review to developing countries*

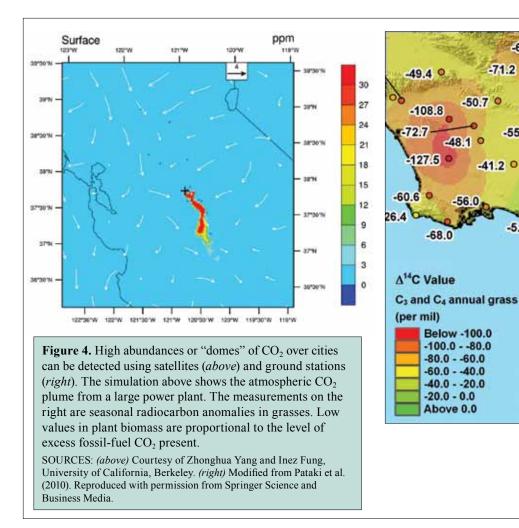**Figure 3.** Sources of greenhouse gas emissions in 2000. In general, energy production and use are the largest sources of emissions for developed countries; whereas agriculture and deforestation are generate the most greenhouse gases in developing countries.

SOURCE: Data from the World Resources Institute.

  - *extending the most stringent inventory methods to the most important greenhouse gas sources in each country*

Costs could be kept down by using the most stringent, accurate methods to calculate emissions from only the largest sources of greenhouse gases in each country. Agriculture and deforestation activities produce the majority of emissions in most developing countries (Figure 3). Implementation of land cover mapping recommended below would reduce inventory costs for these countries.

Improving Independent Estimation of Fossil-fuel CO_2 Emissions

Measurements of atmospheric abundances of greenhouse gases could be used to independently verify self-reported emissions estimates; however, these measurements currently have uncertainties of 100 percent or more at national scales. This is because the transport of emissions through the atmosphere is not well understood, large and incompletely understood background fluctuations of natural emissions obscure the

fraction of emissions caused by human activities, and the observing network is sparse, often missing the urban areas and large industrial sources which generate most emissions. Implementation of the recommendations below would help improve understanding of the transport of emissions through the atmosphere, overcome the background noise generated by the natural variability of the atmosphere, sample the large urban and industrial sources, and provide the capability to verify self-reported estimates of fossil-fuel CO_2 emissions.

- *The National Aeronautics and Space Administration should build and launch a replacement for the Orbiting Carbon Observatory*

The abundance of CO_2 in the atmosphere is highest over emission sources and disperses within a few tens of kilometers. CO_2 created by large local sources such as cities and power plants could have been detected by NASA's Orbiting Carbon Observatory (Figure 4), which failed on

Figure 4. High abundances or "domes" of CO_2 over cities can be detected using satellites (*above*) and ground stations (*right*). The simulation above shows the atmospheric CO_2 plume from a large power plant. The measurements on the right are seasonal radiocarbon anomalies in grasses. Low values in plant biomass are proportional to the level of excess fossil-fuel CO_2 present.

SOURCES: *(above)* Courtesy of Zhonghua Yang and Inez Fung, University of California, Berkeley. *(right)* Modified from Pataki et al. (2010). Reproduced with permission from Springer Science and Business Media.

launch in February 2009. This satellite offers higher precision and a smaller sampling area than any CO_2-sensing satellite already in use, and also offers the ability to sense CO_2 near Earth's surface—qualities needed to monitor large local sources and to attribute their CO_2 emissions to individual countries. The two-year mission would demonstrate that it is possible to monitor large local sources of CO_2 from space and also provide baseline atmospheric data against which to measure future trends.

- *Extend the international atmospheric sampling network to research greenhouse gas emissions over a representative sample of large local emitters, such as cities and power plants, and to fill in underrepresented regions globally, thereby improving national sampling*

Large local sources could also be monitored using atmospheric sampling stations deployed on the land surface (Figure 4). Most stations in the international atmospheric sampling network were deliberately located far from cities and power plants in order to better observe the natural cycles of greenhouse gases. However, adding stations in or around large sources of emissions would provide data for monitoring as well as for "ground-truthing" CO_2 measurements from the Orbiting Carbon Observatory—that is, provide ground data to interpret the satellite measurements. In addition, large areas of the planet, such as Africa and South America, have few measurement stations. Adding atmospheric sampling stations to the undersampled countries with the highest emissions would greatly

improve capabilities to independently verify self-reported emissions estimates.

- *Extend the capability of the CO_2 sampling network to measure atmospheric radiocarbon*

Measurements of radiocarbon (^{14}C) in the CO_2 samples already being collected would allow fossil-fuel CO_2 emissions to be separated from non-fossil fuel emissions—modern organic material contains radiocarbon from cosmic rays and bomb tests, but the radiocarbon in fossil fuels has long since decayed away.

Improving Independent Estimation of Fluxes from Land-Use Sources and Sinks

Measurements of emissions and absorption of CO_2, CH_4, and N_2O from land-use activities such as agriculture and forestry currently have the highest uncertainties in national inventories, commonly greater than 100 percent. Satellite imagery provides an independent check on the activities that create the largest CO_2 emissions from land use. Publicly available Landsat imagery, supplemented with high-resolution imagery which can distinguish areas undergoing logging and forest degradation even down to detecting single trees, could be used to create a gridded map that would allow countries to validate land-use emissions anywhere in the world. Such a map would also help developing countries improve estimates of their dominant emissions source.

- *Establish a standing group to produce a global map of land use and land cover change*

Figure 5. Land-remote sensing images of a portion of Malaysia. Medium-resolution Landsat imagery (*top*) offers a global capability to monitor deforestation and forest degradation, which are responsible for most CO_2 emissions from land use, every 16 days. High-resolution Ikonos imagery (*bottom*) can be targeted to monitor areas undergoing active logging and degradation.

SOURCES: (*top*) NASA Landsat image by Jesse Allen and Robert Simmon. (*bottom*) IKONOS satellite image courtesy of GeoEye. Copyright 2010. All rights reserved.

at least every two years. This will require a commitment to maintaining the continuous availability, in the public domain, of Landsat and high-resolution satellite imagery

Natural emissions of CO_2, CH_4, and N_2O can interfere with the detection of human-made emissions. Research on the natural cycles of these gases and on CO_2 emissions caused by deforestation and forest degradation, CH_4 emissions from rice paddies and cattle, and N_2O emissions from fertilizer application would yield long-term improvements in the accuracy of emissions caused by land use.

- *An interagency group, with broad participation from the research community, should design a research program to improve methods for estimating agriculture, forestry, and other land-use emissions of CO_2, CH_4, and N_2O.*

Implications for an International Climate Agreement

International agreements to limit future greenhouse gas emissions will require that countries be able to monitor and verify emissions. Within a few years of their implementation, the above steps would establish rigorous annual national inventories of greenhouse gas emissions,

Rice paddy agriculture is a major source of CH_4. The areas where paddy rice is being cultivated can be identified using land remote sensing, but research on the biogeochemical cycle of CH_4 is needed to reduce uncertainties in CH_4 emissions from rice production.

enabling every country to estimate the largest sources of emissions—CO_2 from fossil-fuel use and deforestation—to 10 percent uncertainty. They would also provide independent and transparent checks on emissions from these sources with the same accuracy. Finally, targeted research would ultimately lead to improved monitoring and verification of all greenhouse gases.

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