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METHODS FOR ESTIMATING GREENHOUSE GASES FROM LOCAL PLACES

ABSTRACT This paper reports on two efforts to develop methods for quantifying and analysing greenhouse gas emissions from local places. The International Council for Local Environmental Initiatives--Cities for Climate Protection (ICLEI-CCP) campaign and the Association of American Geographers--Global Change in Local Places (AAG-GCLP) project represent independent efforts with differing origins and objectives. There is a rich and dynamic fine structure to the causal patterns that determine the level of greenhouse gas emissions in the society. This fine structure is essentially opaque to national and state-level inventories and analyses, and yet understanding it is necessary to understanding how human communities can be organised and human enterprise structured in environmentally sustainable ways. Simplified inventory methods that account for most but not all emissions, use readily available local data and, most important, inform efforts at emission reduction are currently available for cities and could be made available for larger or more diverse local regions or areas.

Introduction

The human activities that can lead to climate change are very local (Kates & Torrie, 1998; Angel et al., 1998). The major activities are those related to fossil fuel production and burning (manufacturing, electricity generation, transportation, and household heating), to forestry and agriculture (livestock, wetlands, fertilisers, land clearing, timber production), to waste disposal (landfills and incineration), and to ozone-depleting chemical (ODC) manufacture and use. They emit trace greenhouse gases (GHGs) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone-depleting compounds (ODCs) that accrue in the atmosphere and increase positive radiative forcing, warming the surface of the earth. They also emit airborne particles, mainly sulphate aerosols, that decrease positive forcing, and thus act regionally to counter greenhouse warming potential. They also change the land cover of the earth, leading to changes in reflectivity (albedo) that can affect radiative forcing. Taken together, these factories, vehicles, households, fields and animals number in the billions of point sources of emissions, aerosols and land-cover change.

While emissions sources are very local, efforts to identify and measure human-induced greenhouse gas emissions still focus very much on the global. These efforts arose first from the needs of scientific modellers of global climate, and later from the developing inter-governmental effort to assess the problem (under the Intergovernmental Panel on Climate Change (IPCC) process: Bolin, 1998) and then to allocate national responsibility under the 1992 Framework Convention for Climate Change. However, action to reduce greenhouse gases is never global, and despite much rhetoric is rarely national, but is mostly local. Global agreements and national regulations and incentives may be needed to encourage or require such abatement, but abatement actually occurs at the local level when people and their organisations modify their behaviour, change their activities, and employ different technologies. Critical for encouraging such action is a basic knowledge of the size and content of the bundle of greenhouse gases that are emitted by local places, people and institutions.

The widely used methods developed for estimating greenhouse gases at the global and national levels are not readily applied at the local level. In part, this is so because the greater the spatial aggregation, the less there is a problem of emissions allocation. At the global level, it is sufficient to assume worldwide diffusion of the major gases regardless of their point sources of origin. Production and consumption of fossil fuels are documented in national energy balances and it is relatively simple to produce national inventories of energy-related carbon dioxide emissions from such data. There is more uncertainty in the data and methodology for estimating non-combustion sources of carbon dioxide and of the other greenhouse gases, but the methods and data that do exist are most highly developed and collected at the national level.

We believe that people and organisations need to know how much they are responsible for greenhouse gas emissions in order to appreciate their impact on global climate change and to understand their opportunities to reduce that impact. This paper reports on two efforts to develop methods to examine greenhouse gas emissions at a local level--the level at which people can control and potentially reduce emissions.

USEPA State Inventories

A partial effort to apply the current method for greenhouse gas emissions accounting at the sub-national level has resulted from the United States Environmental Protection Agency (USEPA) financial and technical assistance for states to compile comprehensive GHG inventories, state action plans and innovative demonstration projects. The EPA methodology is based on the approach established by the Intergovernmental Panel on Climate Change (IPCC/OECD/IEA, 1995). The IPCC methodology was designed to be used in nations throughout the world with a wide range of input data. The USEPA has produced a 325-page State Workbook (USEPA, 1995b) with instructions for calculating emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and some of the ozone-depleting compounds (HFC-23 and PFCs). Because detailed data concerning energy-consuming activities are available for the USA, the EPA methods are more comprehensive than those established by the IPCC (USEPA, 1995b). Future versions of the IPCC and EPA protocols may include simplified methods for data-poor nations but the trend is currently toward developing more detailed methods for areas which possess a large amount of data at the consumption or activity level (Wiley Barbour, USEPA Office of Policy, Planning, and Evaluation, personal communication, 1998).

Unlike many air pollutants, greenhouse gas emissions are not measured directly, but are inferred either from the use of materials that yield such gases or from processes that produce such gases. The materials approach is exemplified by the calculation of CO_2 released from the combustion of coal in power plants. Data on coal consumption by utility exist at the state level, so it is a simple matter of multiplying those values by appropriate coefficients to account for the carbon content of the coal and the combustion efficiency of the boiler. The process approach is exemplified by the calculation of CO_2 emissions from the production of cement, in which the amount of CO_2 released during the calcining process can be estimated as the product of the output of the plant (in tons of cement) and the emissions of CO_2 per ton of cement produced (USEPA, 1995b).

These 'coefficient-based' methods result in state inventories of greenhouse gas emissions that are summarised in matrix form, showing different gases in tons/year originating from sources that include both materials (fossil fuel and biomass) and activities (specific industrial production processes, agriculture, waste disposal). Emissions are further subdivided by source activities: commercial, industrial, residential, utilities, transportation, and fuel production and distribution. All the emissions are then converted to standard units of equivalent tons of CO_2 by using IPCC 'global warming potentials' that account for the different warming potential for each of the greenhouse gases.

The International Council for Local Environmental Initiatives--Cities for Climate Protection (ICLEI-CCP) campaign and the Association of American Geographers--Global Change in Local Places (AAG--GCLP) project represent independent efforts with differing origins and objectives, contrasting experiences in choices made, but similar conclusions as to methods for estimating greenhouse gases in local places.

ICLEI--Cities for Climate Protection

In 1991, the International Council for Local Environmental Initiatives launched the Urban CO_2 Reduction Project to encourage local governments to reduce greenhouse gases. A collaborative research effort was undertaken in 14 North American and European cities to develop and test methods needed for local governments to undertake greenhouse gas emission-reduction strategies. Based on that experience, in 1993 ICLEI established the Cities for Climate Protection Campaign to accommodate the growing number of local governments committed to greenhouse gas emission reduction. By early 1998, the rapidly growing programme had over 240 members worldwide with a combined population of 100 million that accounted for more than 5% of global CO_2 emissions (ICLEI, 1997a).

Cities that participate in the campaign undertake to complete five key tasks or milestones, namely, conducting an energy and emissions inventory; preparing a forecast of future emissions; setting an emissions reduction target; formulating a local action plan to achieve the target; and implementing policy measures and programme to reduce emissions of carbon dioxide and methane.

Supporting these tasks is a significant science effort designed to produce tools of analysis that allow cities to readily track their own emissions, forecast changes over time, and assess the potential impact of a diversity of technical and policy measures to achieve their selected targets. (Torrie, 1996; Torrie & Skinner, 1996). This paper draws upon the effort to create emissions inventories, the first of the milestones, now completed by 90 local governments (ICLEI 1997a, 1997b).

Global Change in Local Places

In 1995, the Association of American Geographers, with support from the Mission to Planet Earth Program of NASA, sought ways to bring the scientific competence and local knowledge that is found in many colleges and universities to address the linkages between local places and global climate change. At three sites in the United States, teams from Appalachian State University, Kansas State University and the University of Toledo study how local places contribute to global change through their emissions, how those contributions change over time, what drives such changes, what control local interests have over such driving forces, and how such efforts are likely to be locally initiated and implemented.

The three study sites, each of which approximates an area of one equatorial degree of latitude by one degree of longitude (~ 13 000 km^2) represent diverse sources and sinks of greenhouse gases in the United States. The Blue Ridge-Piedmont of North Carolina encompasses a forest border and a rapidly growing set of rural-urban activities. The High Plains-Ogallala of Southwest Kansas is thinly populated but with intensive agriculture, livestock and natural gas production drawing on an ancient but declining aquifer. The Great Lakes-Manufacturing region of Northern Ohio is still in the midst of a massive restructuring of a rust belt industry closely linked to automobile production. This paper draws upon the methods used to measure or estimate greenhouse gas emissions primarily from the Blue Ridge-Piedmont study site (ASU 1997), but only slight modifications of these methods were made for the other two study sites.

Choices

The greenhouse issue can be a very complex one, and there is no end to the minutiae of detailed information that is necessary to fully characterise greenhouse gas emissions and emission reduction opportunities. Estimating emissions for local places requires many choices. Three major choices are those of purpose, locale and emissions.

Why Estimate GHG at the Local Level?

In the case of the ICLEI--CCP methodology, the purpose of the local inventory of greenhouse gas emissions is to help identify and quantify the most important sources of greenhouse gas emissions in communities and to help identify and quantify the most effective opportunities for reducing those emissions. Because local governments directly or indirectly influence so many of the factors that determine greenhouse gas emissions (Torrie, 1993; Jessup & Torrie, 1996), they require knowledge of the local levels and patterns of those emissions to be able to design effective local strategies for emission reduction. The ICLEI--CCP campaign is a performance-based initiative and it requires methods than can be widely applied by individuals working in local governments who are primarily interested in pragmatic techniques that can help them design effective emission reduction policies and programmes. This criterion of practicality affects every aspect of the design of the ICLEI/CCP framework for municipal greenhouse gas emissions inventories. There is a also strong emphasis on using and maintaining community data sources.

The performance-based focus of the ICLEI--CCP campaign has many important implications for the analytical approach used in developing greenhouse gas inventories. The emphasis is on carbon dioxide from fossil fuel combustion and methane from landfills; less importance is placed on other gases and on sources that are small in most urban environments. An end-use-oriented approach is taken in which power plant emissions are pro-rated over kilowatt hours of electricity use, but full fuel-cycle analysis is not generally applied to other sources.

The ICLEI--CCP methodology includes both emission inventories and emission reduction measures quantification, but the priority is on emission reductions. For example, when considering methane emissions from landfilled organic waste, the common approach is to determine the current atmospheric emissions of methane (as done in the EPA state inventories) based on the historical quantities of waste in the landfill and the current actual methane emission rates (net of recovery) at the surface of the landfill. This is the appropriate method for determining actual emissions in the current year or for analysing the feasibility of methane recovery options, and the ICLEI/CCP methodology includes methods for doing such calculations. Cities, however, are also very interested in the methane emissions that can be avoided through measures that reduce the amount of carbonaceous waste going to the landfill in the first place (e.g. garden composting, rubbish reduction and recycling) and this requires an inventory method based on the future methane emissions potential represented by waste being sent to landfill today; the ICLEI--CCP methodology emphasizes this approach.

The purpose of the AAG--GCLP project is to understand the causes and dynamics of greenhouse gas emissions at the local scale, the capacity of local people to affect them and, more generally, to understand how scale matters. In its effort to link to the international global change research effort it takes as a starting template the EPA state inventories but modifies these as needed to try to answer scientific questions.

For example, because one of the research questions is to estimate the portion of greenhouse gases emissions that can be reduced by local action, emissions created beyond the local place for products consumed locally need to be considered--a difference ignored for the most part by the EPA state inventories. The AAG--GCLP project thus creates two sets of emission inventories, as described below, one using the categories of the EPA state inventory and one focused on groups of end-users of emission-generating products.

The ICLEI--CCP and AAG--GCLP initiatives have different but overlapping purposes, and this leads to similar conclusions in one purposeful choice--emission inventories need to be in a form that facilitates emissions reduction by those that produce emissions or consume emission-generating products.

What is a Local Place?

A first step in developing a local emissions inventory and emission reduction analysis is to define the physical territory of a local place. There is, of course, no general definition of local, other than being the opposite end of a continuum of space from global to local. The differing objectives of the ICLEI--CCP and AAG--GCLP efforts lead to different definitions of local places and different problems arising from such choices.

For ICLEI--CCP, the choice is urban places, some as small as the smallest jurisdiction that has made the commitment to tracking and reducing emissions. Municipalities typically approach the task of greenhouse gas emission inventory and emission reduction analysis in terms of their political boundaries. However, a more appropriate choice of boundaries is that of a regional or metropolitan area that links municipalities that share a common central city, economic focus, transport net and utility services.

The boundary is especially important for analysis of transport-related emissions. For a metropolitan region, or for a city with boundaries that encompass most of the residential and business activity in the region, there is a high degree of 'self containment'--most of the trips that begin in the region also end in the region. This makes for easier and more useful analysis of the transportation sector. The regional metropolitan boundary can also facilitate the tracking and analysis of methane emissions, and quantifying emissions from water and sewage treatment operations, services that are very often delivered by regional or metropolitan governments. The regional boundary can also facilitate a more holistic analysis of carbon dioxide emissions as it allows for increasing density in the urban core to be treated as an emission reduction option, even though such urban densification may increase total emissions in the core city.

The AAG--GCLP sites are much larger--the equivalent of 1 degrees square (equatorial latitude and longitude), or about 13 000 km^2 (about the size of Connecticut). As a research study, the 1 degrees square size of the GCLP study areas was chosen as an arbitrary starting point for investigating scale issues, large enough to assure diversity of emission sources and to link to the grid size used in global climate models. As an initial effort, sites were desired that between them provided estimation experience with most greenhouse gases and most sources of emissions. Global climate models currently use 5-10 degrees square grids but finer grid sizes are in the offing as well as efforts to downscale current models. Thus the study wanted to ask what could be learned from finer scales if they become practicable (Easterling et al., 1998).

The actual boundaries of these large local places, however, follow the political boundaries of US counties for data availability, and this allows analysis within each study site of smaller county units. The North Carolina site, for example, comprises 12 counties and data are collected separately for each. Thus at the county level, the AAG--GCLP local place size converges with the cities, counties and metropolitan regions of ICLEI--CCP.

Which Emissions?

Differences in objectives between ICLEI--CCP and AAG--GCLP also lead to differences in the types of emissions inventoried. For the pragmatic ICLEI--CCP approach only the most important sources of greenhouse gas emissions are included. Thus the ICLEI--CCP effort concentrates on CO_2 from energy and methane from landfills, believing that it is more important to encompass all the 'big terms' than to have a completely comprehensive framework that is not practical for municipalities to use.

Just the reverse approach was initially adopted by AAG--GCLP research, which started with the objective of examining the relevance of all significant gases, both to encompass sources and activities not found in cities, such as agriculture or natural gas extraction, and to study problems involved in estimating them in local areas. Thus the project not only estimated the full range of GHGs used in state inventories (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone-depleting compounds: HFC-23 and PFCs) but explored some of the emissions that were omitted in state inventories.

Standard IPCC/EPA inventory protocols omit or underestimate some important sources of greenhouse gas emissions, including chlorofluorocarbons (CFCs) and methane. Because CFC production, a major source of ozone-depleting chemicals, has been curtailed and will eventually be eliminated by the Montreal Protocol, those emissions are not calculated under the IPCC Guidelines (IPCC/ OECD/IEA, 1995). However, CFCs continue to contribute significantly to radiative forcing, notwithstanding the ongoing scientific research into their net effects. When evaluated using only their direct global warming potentials, CFCs represent 27% of total greenhouse gas emissions in North Carolina (ASU, 1997); even after allowing for the offsetting impact of their indirect effects, they remain an important contributor to greenhouse gas emissions in many local places. Procedures have been developed for estimating CFC consumption at the national level, but no method currently exists for accounting for CFC production or consumption at the local level (McCulloch et al., 1994).

Emissions of methane during the production and distribution of natural gas come from a variety of sources, including field production, processing plants, storage facilities, transmission facilities, compressor stations and distribution systems. Greenhouse gases are released at every stage in the production and delivery of natural gas through combustion of fuels, flaring, and fugitive emissions from leaks and pipe evacuation for maintenance. There is greater uncertainty about the amounts of methane released in natural gas production and delivery than in any other sector of emissions. Work in the Ogallala--High Plains GCLP study area indicates that emissions from pipeline purging and fugitive emissions are significantly higher than the EPA protocol indicates.

With respect to biomass, the IPCC/EPA protocols include an emissions inventory category for land-use change. If biomass is harvested and burned faster than it is replaced then the net carbon flux from the imbalance is recorded in the land-use change category. The CO_2 emissions from biomass burning are not themselves included in the combustion-related emissions. However, because biomass burning can and does make such a significant contribution to energy supply (thereby displacing what would otherwise be fossil fuel combustion), local methods for greenhouse gas emissions analysis often track CO_2 emissions from biomass combustion, but leave it out of the inventory total.

Problems and Solutions

Within the bounds of their major choices, both projects had to cope with missing data for cities and counties, with the allocation of emissions produced or consumed elsewhere, with the replication of inventories to other sites and backwards or forwards in time, and with the simplification of the inventory process to encourage its adoption.

Missing Data

Surprisingly, moving downscale makes data more difficult to obtain than at higher levels of aggregation. Data are either not collected by public or private sources, are withheld as proprietary or made available only at great expense, and when available, do not match the area under study and must be allocated to it with much difficulty. Examples abound: fossil fuel consumption data, the major single variable in emissions, are not available locally; electricity generation and consumption data rarely fit local areas, and utilities are becoming less willing to share such information when they do have it; estimates of ozone-depleting compounds are based on national production data.

The quantification of transport-related emissions exemplifies the difficulty of local greenhouse gas emissions analysis and also illustrates the different solutions applied by the AAG--GCLP and ICLEI--CCP methods. Transport-related emissions account for nearly a third of all greenhouse gas emissions in the USA (USEPA, 1995a), but can comprise more than 60% of greenhouse gas emissions in some urban environments. Data needed to calculate carbon dioxide emissions directly from gasoline or diesel fuel consumption or sales do not exist at the county level in any of the three AAG--GCLP study sites and are not available anywhere at the local level.

Some states have accurate fuel sales databases at the county level, but there are significant boundary issues to be considered. Even if fuel sales data are available for a jurisdiction, they are not necessarily accurate indicators of fuel consumption in the same jurisdiction--transport fuel purchased in the jurisdiction may be burned elsewhere and transport fuel burned in the jurisdiction may have been purchased elsewhere. Retail gasoline and diesel sales data are often available from private sources, and they are available down to the individual postal code and address level, but the issue remains of the mismatch between fuel sales and fuel consumption data. Further, retail sales of transport fuels are only part of the picture and do not include the very considerable portion of transport fuel which is sold on the wholesale market for use by government and corporate vehicle fleets.

In both the USA and Canada, detailed energy commodity statistics are available at the state and provincial levels, but such data are not generally collected or compiled for local places such as municipalities or counties and other sources and methods must be used. A common method is to simply apportion national or state/provincial level data to cities or counties according to local population or economic activity, but this method fails to support the central focus of both the ICLEI--CCP and AAG--GCLP initiatives--to understand local variability. Both the ICLEI--CCP and AAG--GCLP methods utilise a combination of 'bottom-up' estimates and 'top down' normalisation to achieve characterisations of local emissions that can yield insight into the dynamics of greenhouse gas emissions at the local level.

The ICLEI--CCP method, with its emphasis on emission reductions over inventories, utilises a causal factor approach that combines levels of energy using activity, technological efficiency and fuel shares. Data on total fuel and electricity sales to different sectors are used to estimate total emissions in the community and the causal factor approach is relied upon to estimate the potential for emission reductions and transport emissions and emission reductions. In addition, data on the total volume and mix of organic waste being sent to landfill is used to estimate the future methane emissions associated with the current year's production of waste.

For the difficult transport sector, in the ICLE--CCP protocol, only road transport and public transit are included in the scope of the inventory and the emission reduction plan. Emissions are estimated on the basis of a simple five-factor formula that includes the number of trips, the average length of trips, vehicle occupancy (not applicable for freight movement), vehicle fuel efficiency, and emissions per unit of fuel (which varies depending on the fuel being used). Traffic count, mode share and transport survey data commonly available in cities are combined with state or national averages for vehicle fuel efficiencies and fuel market shares to estimate the values for the five factors. While there is still a great deal of uncertainty in the calculation of transport energy use and emissions on the basis of such input data, the method does provide a consistent basis for estimating transport-related emissions, and it is particularly well suited to the primary objective of the ICLEI--CCP project: the identification and quantification of emission reductions from specific measures. For example, if person-miles of travel decline by 10% then, all else being equal, so will transport greenhouse gas emissions. Even if the absolute value of total emissions is uncertain, the method is reliable for quantifying the impact on emissions of changes in the individual factors.

In the AAG--GCLP method, the major surrogate used is carbon monoxide air pollution data, which in the USA are available for local areas. More specifically, the AAG--GCLP method uses monitored or modelled carbon monoxide (a legally defined pollutant) as a surrogate for carbon dioxide, based on the assumption that for specific sources or sectors the emission of CO_2 is proportional to the emissions of CO. Carbon monoxide emissions are estimated or calculated for individual point sources--industrial plants, commercial-institutional users, and power plants--and these emission data are reported directly to the EPA (USEPA, 1996) and these specific point sources were used to estimate industrial, commercial and utility emissions. In the cases of residential and transportation based CO emissions, which arise from hundreds of millions of sources, estimates are made on the basis of models of emission rates from different categories of households or vehicles. Thus in the case of transport AAG--GCLP used readily available data--vehicle miles travelled by county--as input into a model used to estimate CO and other vehicle emissions (EPA Mobile 5a). The county estimates of CO were then used to apportion state fuel sales-derived CO_2 estimates to the county level.

Allocation

Estimating local emissions is difficult conceptually because some emissions take place at the point of final consumption (e.g. the burning of fossil fuels for heat or motive power) and some emissions are separated in space or time from the point of final consumption that is causing the emissions (e.g. power plant emissions related to the end use of electricity, oil and gas production and transmission emissions related to the final consumption of fuels, methane emissions in the future or at distant landfills that are related to organic waste disposal by households and businesses). Ultimately, all greenhouse gas emissions could be linked to final consumption behaviour, but the extent to which such a principle should be and can be applied is a central consideration in the methodology of local emission inventories. Inventory methods for local emissions must address the problem of when and how to allocate emissions that are produced outside the local place and how to distribute emissions within the local place.

While it can be argued that in principle final consumers should be accountable for the 'full cycle' of emissions their activities generate, in practice there are many difficulties related to data collection, conceptualisation and the avoidance of emissions double counting. The practical principle of allocating emissions in accordance with the ability to reduce emissions can be effective in determining the most useful method. The two most important types of off-site carbon dioxide emissions are those incurred in the production and transport of fossil fuels and those incurred in the production and transport of electricity consumed in the municipality but generated outside the community.

In a so-called 'full fuel cycle emissions analysis', in addition to the emissions at the point of use, all the emissions generated in the upstream activities, from the oil well to the gas tank, or from the natural gas field to the home furnace, are allocated to the point of final consumption. Typically, the resulting 'full cycle' emission coefficient is about 10-15% higher than if only the point-of-enduse emissions are included. Neither the AAG--GCLP nor the ICLEI--CCP projects have adopted full-cycle emissions coefficients in their inventory methods, although some members of the Cities for Climate Protection do opt for this approach. In the case of the ICLEI--CCP project, the marginal benefit of computing and applying full-cycle coefficients did not seem justified by the benefits: the AAG--GCLP rejection of full-cycle coefficients was based on a desire to avoid double counting.

In the case of electricity, greenhouse gases are not emitted at the point of final consumption but at the place where the electricity is generated, and then only if the electricity is generated from fossil fuel combustion. Because of the importance of local places as consumers of electricity, both ICLEI--CCP and AAG-GCLP include power plant emissions associated with the local consumption of electricity. Care is exercised not to double-count these in the case of electricity generated within the local place. Annual average emission coefficients are used for computing emissions associated with end-use electricity; a simple method for applying marginal coefficients for measures analysis has been developed by the ICLEI team, but it is not employed for inventory purposes (Torrie Smith Associates, 1997b).

Within a local place, both ICLEI--CCP and AAG--GCLP seek to allocate emissions in ways such that economic enterprises, local government, institutions and householders can be informed as to their share in creating emissions and their capacity to reduce them. Standard international, national and even state inventories are not readily disaggregated for that purpose as they mix materials and activities and producers of emissions and consumers of emission-generating products. For example, household emissions are found under five different categories. Electricity consumption is estimated within a category of utilities, household travel emissions within a transportation category, household fuel consumption for heating within a residential category, household waste within waste in municipal landfills, and household ODCs, if estimated at all, are prorated from national production figures.

ICLEI--CCP retains the standard categories of residential, commercial and institutional, transport, and industrial and allocates total energy use of any particular fuel in each major energy-consuming sector. In its advanced applications, the ICLEI--CCP method then includes a further breakdown into subsectors (types of residential houses, types of commercial buildings, transportation of people vs. goods, individual industries, etc.). For each sector (or subsector) a basic unit of activity is defined: the household for the residential sector, the square meter of building floor area for the commercial and institutional building sector, person-miles or ton-miles in the transport sector, and dollars of output or tons of output in the industrial sector. The framework is flexible and any level of disaggregation can be used.

AAG--GCLP has addressed these same problems by reallocating county-level greenhouse gas emissions (with the exception of ODCs) to 'end-user categories'. These categories are: agricultural, residential, and industrial/commercial (collapsing commercial and industrial into a single category because of the absence of separate data). To illustrate, in order to inform households as to their real share of local place emissions, all or household-related portions of the following emission sources were placed in the end-user category of 'residential': waste incineration, sewage, landfills, fossil fuel use, biomass, electrical utility, nonhighway vehicles, and highway vehicles.

Ozone-depleting compounds (ODCs) were not accounted for in the end-user analysis because no protocol exists which would allow accurate estimation of ODC consumption at the county level. However. in accordance with the EPA protocols, the AAG--GCLP team did account for the ODCs not covered by the Montreal Protocol: PFC-CF4, C2F6 and HFC-23. The AAG--GCLP research team is currently working on a protocol for estimating ODC consumption at the local scale by evaluating industrial consumption of ODCs together with domestic and commercial uses of refrigeration and air conditioning.

Replication

Both ICLEI--CCP and AAG--GCLP have sought to replicate their studies in space and time. To date, over 90 ICLEI--CCP cities report that they have completed emission inventories and some 64 cities have provided their detailed data to the project secretariat (ICLEI, 1997a). Such replication has been possible because the inventory framework was designed to be used by cities with different populations, economies and emission profiles and to support as much or as little data disaggregation as the municipality was willing or able to put into it. Municipalities will be able gradually to add detail and disaggregation as they identify the priority emission reduction targets for their community.

Inventories should also be replicated in time. An important purpose of the ICLEI--CCP framework is to allow tracking of greenhouse gas emissions over time, so that future inventories can be compared with confidence with earlier years and so that the success of emission reduction programmes can be tracked and evaluated. Most cities chose the year 1990 for their initial inventory. Some 54 cities have also begun to replicate the inventories in time and have also created forecast inventories for future years against which they can gauge their progress.

In the context of the ICLEI--CCP project, a key reason for developing a practical and standardised method is so that local governments with varying levels of time and resources will be able to maintain and regularly update the greenhouse gas emissions inventories. The amount of time and resources that cities can be expected to invest in maintaining a greenhouse gas inventory is a real constraint on the level of detail and sophistication that can be introduced to the framework. Some cities will be more motivated than others, and as the consequences of global warming and the multiple benefits of greenhouse gas reduction strategies become more widely appreciated the level of motivation can be expected to increase, but cities will always be dealing with a multitude of other issues of equal or greater urgency and importance. The ICLEI--CCP project prefers an analytical framework that is used to a more complex and sophisticated one that is not.

A major goal of the AAG--GCLP project is to develop a protocol for local area studies of global change--guidelines for local studies that will yield comparable results. Emissions inventories are the initial part of such a protocol. To facilitate replication, a set of spreadsheets was developed at the North Carolina site and these were tested and used successfully at the sites in Ohio and Kansas. Subsequently, a regional research group at Penn State University has employed the same spreadsheets to calculate emissions for a 1 X 1 degree region in the Susquehanna River basin of Pennsylvania.

AAG--GCLP has also sought to replicate its studies over time, initially backcasting in time from 1990 to 1980 and 1970 in order to identify the dynamics of change in emissions in each of the study sites (Easterling et al., 1998). For 1970 and 1980, critical data are unavailable for major emissions categories such as transport and industrial/commercial emissions. The GCLP research team developed a simple method for estimating historical emissions based on activity levels in each of those categories. Addressing the future, the group is in the process of calculating emissions for 1995 and has completed projections for 2000, 2005 and 2010.

Though the AAG--GCLP method is clearly replicable, the current EPA state-level method is too complicated (the workbook is 325 pages) to apply to localities, too data and labour-intensive even for the USA and surely for developing countries. Completion of the inventory for North Carolina required three person-years of effort, including research time to develop solutions for the various problems described but not including the additional time spent by government officials to supply data and procedural advice. In many cases, the EPA protocol requires a tremendous amount of effort to calculate emissions of little consequence. An example is the calculation of methane emissions from domesticated animals. To complete such an inventory requires a census count of herd size of dairy cattle (by three age classes), beef cattle (by six age, sex and herd type classes), sheep, goats, pigs, horses, mules and asses. For each of those classes, an estimate of emissions is made and the results summed. For the North Carolina emission inventory, with its large agricultural sector, this part of the inventory work took approximately 15 person-months of labour but accounted for less than 1% of the total emissions inventory.

Simplification of Methods to Facilitate Adoption

Simple but relatively accurate methods for estimating greenhouse gas production from small to large areas are needed. The AAG--GCLP research team has devised a simple protocol that requires approximately one person-month of data collection and accounting work for the estimation of greenhouse gas emissions from a 1 degrees square area. For the Blue Ridge-Piedmont study area, the simplified method yielded results that were within 5% of the values obtained from the modified (complex) IPCC/EPA inventory.

The standardisation and simplification of emission inventory and emission reduction quantification methods has been a priority objective for the ICLEI-CCP project, and they have made the most progress in this regard. After first developing a standardised protocol for quantification in the Cities for Climate Protection Campaign (Torrie & Skinner, 1997), ICLEI has now developed user-friendly, Windows-based software that supports that protocol. The software includes extensive on-line help, automatic unit conversions, default values for emission coefficients and other variables, pre-formatted reports, illustrated examples and computational tips, and step-by-step guides for conducting emissions inventories and reduction measure quantification for both community-wide and 'in-house' or corporate analyses (Torrie Smith Associates, 1997b). The software has been adopted by CCP cities in the United States, Canada and Australia, and future plans include adaptations for Europe, Asia and South America.

A Sample Application

Tables 1 and 2 provide a glimpse of the types of results being produced by the AAG--GCLP and ICLEI--CCP methods, respectively. In Table 1, the emission inventory is shown for the Blue Ridge-Piedmont study region, including the percentage contribution made by each of the gases and each of the major sources. For comparison, the corresponding percentages are shown for the inventory of the entire state of North Carolina. (See Easterling et al., 1998, for a full comparison with other study sites, states and the nation.) The Blue Ridge-Piedmont inventory shows a smaller contribution from transport sources than for the state as a whole, but this is partly due to the more comprehensive scope of transport sources included in the state inventory as compared with the regional inventory. Also, the greenhouse gas emissions from land-use changes have not been included in Table 1. Such emissions offset the state inventory by more than 7%, but because the corresponding calculations have not yet been completed for the study area, to facilitate comparison, the land-use change entries for the state have been left out of the results in Table 1.

A comparison of the percentage columns for the region vs. the state begins to reveal the types of variation and insight that emerge from local emissions inventories, variations that are essentially invisible at higher levels of aggregation. Of course such results must be interpreted carefully, but it is precisely that type of careful interpretation (which is beyond the scope of this short paper on methods) that promises so much new insight into the local dynamics of greenhouse gas emissions (Easterling et al., 1998).

Table 2 summarises inventory data for a selection of the cities in the ICLEI--CCP project, presented on a per capita basis to facilitate comparison. In this case, the local places are much more urban than in the AAG--GCLP study regions; indeed, the inventories are for cities. Also, the data in Table 2 relate only to the carbon dioxide emissions from fuel and electricity. Landfill methane, while typically responsible for 7-15% of the total global warming potential of city emissions, was left out because consistent data are not yet available for all the cities.

The focus on the urban environment in the ICLEI--CCP data amplifies the observed variations in the levels and patterns of emissions both among the cities and between cities and larger places. It is the revelation of these variations that makes methods for the analysis of local greenhouse gas emissions such potentially powerful tools for addressing the challenge of climate change.

Conclusions

Despite differences in objectives and context, two independent efforts arrive at four important and similar conclusions based on their overall experience in developing local greenhouse gas emissions quantification methods:

(1) Emissions inventories should serve to inform efforts to reduce greenhouse gases by local action.

Thus inventories need to be disaggregated in ways such that economic enterprises, local government, institutions and householders can be informed as to their share in creating emissions and their capacity to reduce them. Standard international, national and even state inventories do not readily elucidate the local dynamics of greenhouse gas emissions; local methods are required to support local policies and programmes.

(2) As the area under study diminishes, the difficulties posed by boundary problems increase. In principle, local producers and consumers should be accountable for the full cycle of emissions their activities generate, but there are many conceptual difficulties and data problems in applying this principle in practice. By focusing on the objective of developing methods that help local organisations and individuals identify how they can alter their practices, investment patterns and technological choices to reduce greenhouse gas emissions, methods can be developed that are both pragmatic and theoretically sound.

(3) The uniform collection and dissemination of data needed for emission inventories does not address the needs of local places. The single most important change required is to have a uniform system for reporting local sales, deliveries or consumption of fossil fuels. Much of this is clearly within the capability of current data-collection systems of most industrial countries.

(4) To be useful, replicable and maintainable, methods for local emission inventories need to be relatively simple. Given the absence of required local data, the methods currently used by standard international, national and even state inventories are too complex, too labour intensive and too skill intensive to be widely used. Simplified inventory methods that account for most but not all emissions, use readily available local data and, most important, inform efforts at emission reduction, are currently available for cities and could be made available for larger or more diverse local regions or areas.

Already, these and other tentative efforts to develop and apply a methodology for the analysis of greenhouse gas emissions at the local level have shown that there is a rich and dynamic fine structure to the causal patterns that determine the level of greenhouse gas emissions in the society (Easterling et al., 1998). This fine structure is essentially opaque to national and state-level inventories and analyses, and yet understanding it is necessary to understanding how human communities can be organised and human enterprise structured in environmentally sustainable ways.

TABLE 1. Emissions inventory and global warming potential (in '000 short tons) for the Blue Ridge-Piedmont study region

Legend for Chart:

A - Emission source category
B - CH_4
C - CH_4 as CO_2 equiv.
D - CO_2
E - N_2O
F - N_2O as CO_2 equiv.
G - ODC as CO_2 equiv.
H - Total CO_2 equivalent
I - Percentage of study region
J - Percentage of corresponding North Carolina state inventory

A	B	C	D	E	F	G	H	I	J
Fossil fuel consumption	1.1	23.1	16,172.6	0.5	130.6	--	16,326.3	90.2%	85.2%
Commercial/institutional	--	--	523.6	0.0	0.1	--			

	523.7	2.9%	2.6%
Industrial/manufacturing	0.0	0.1	2,169.6
	0.01	1.9	--
	2,181.6	12.1%	16.4%
Residential	0.0	0.1	828.7
	0.0	10.2	--
	839.0	4.6%	4.0%
Utilities	0.0	1.1	7,880.3
	0.1	24.2	--
	7.905.6	43.7%	32.4%
Transportation	1.0	21.9	4.770.3
	0.3	84.2	--
	4.876.4	26.9%	29.9%
Biomass fuel consumption	4.4	96.5	--
	0.1	30.5	--
	127.0	0.7%	0.5%
Residential	4.4	96.0	--
	0.1	24.6	--
	120.6	0.7%	0.5%
All other	--	0.5	--
	0.0	5.9	--
	6.4	0.0%	0.0%
Production processes	--	--	--
	--	--	432.3
	432.3	2.4%	3.2%
Lime processing	--	--	--
	--	--	--
	--	0.0%	0.6%
Ozone-depleting compounds (ODC)	--	--	--
	--	--	432.3
	432.3	2.4%	2.7%
Agriculture and livestock production	20.1	441.2	36.1
	0.3	83.1	--
	560.5	3.1%	6.5%
Domestic animals	9.6	212.2	--
	--	--	--
	212.2	1.2%	0.6%
Animal manure management	10.4	229.0	--
	--	--	--
	229.0	1.3%	5.0%
Fertiliser use/agricultural liming	--	--	36.1
	0.3	83.1	--
	119.3	0.7%	0.9%
Waste disposal, treatment, & recovery	29.1	640.4	13.8
	0.0	1.1	--
	655.3	3.6%	4.5%
Landfills	28.4	624.9	--
	--	--	--
	624.9	3.5%	4.0%
Agricultural and other waste			

incineration, sewerage treatment	0.7	15.4	13.8
	0.0	1.1	--
	30.4	0.1%	0.5%
Total emissions	54.6	1,201.3	16,222.5
	0.9	245.3	432.3
	18,101.4	100.0%	100.0%
Percentage of regional total in equiv, CO_2	--	6.6%	89.6%
	--	1.4%	2.4%
	100.0%	--	--
Corresponding percentage from state inventory[*]	--	11.0%	84.0%
	--	2.0%	2.9%
	100.0%	--	--

Note: * The North Carolina State inventory totals 113.7 million tons. At 18.1 million tons, the Blue Ridge-Piedmont study area represents about 13.5% of the state totals.

TABLE 2. ICLEI Cities for Climate Protection per capita CO2 emissions from a sampling of cities (all data for 1990 or 1998 base year; metric tonnes per capita)

Legend for Chart:

A - City
B - Oil fuels
C - Nat. gas
D - Coal
E - Electricity
F - District heat
G - Total
H - Percentage of city's total energy-related emissions

A	B	C	D	E	F	G	H
Residential sector							
Denver	0.02	2.07	--	4.00	--	6.09	27%
Minneapolis/St Paul	0.01	2.09	--	2.63	--	4.73	27%
Toronto	0.18	2.79	--	0.78	--	3.75	34%
Portland	0.48	0.43	--	0.30	--	1.21	13%
Chula Vista	--	0.70	--	0.97	--	1.67	23%
Helsinki	0.06	--	--	0.74	2.32	3.12	38%
Copenhagen	1.07	0.21	--	0.60	2.02	3.90	52%
Bologna	--	1.12	--	0.55	--	1.67	29%
Ankara	0.37	0.02	0.99	0.34	--	1.72	45%

Commerial Sector				
Denver	--	2.20	--	--
		7.00	9.20	40%
Minneapolis/St Paul	--	1.02	--	3.82
		--	4.84	28%
Toronto	--	1.75	--	1.93
		--	3.68	34%
Portland	0.17	0.35	--	0.27
		--	0.79	9%
Chula Vista	--	0.17	--	0.44
		--	0.61	9%
Helsinki	--	--	--	1.01
		1.14	2.15	26%
Copenhagen	0.21	0.01	--	0.41
		1.41	2.04	27%
Bologna	0.12	0.15	--	0.65
		--	0.92	16%
Ankara	0.40	--	0.22	0.38
		--	1.00	26%
	--	--	--	3.82
		--	9.20	40%
	--	--	--	1.93
		--	4.84	28%
	--	--	--	0.27
		--	3.68	34%
	--	--	--	0.44
		--	0.79	9%
Transportation sector				
Denver	5.44	--	--	--
		--	5.44	24%
Minneapolis/St Paul	7.09	0.19	--	--
		--	7.28	42%
Toronto	2.30	0.09	--	0.01
		--	2.40	22%
Portland	6.09	--	--	--
		--	6.09	67%
Chula Vista	3.85	--	--	--
		--	3.85	54%
Helsinki	2.18	0.01	--	0.05
		--	2.24	27%
Copenhagen	1.20	--	--	--
		--	1.20	16%
Bologna	1.49	--	--	--
		--	1.49	26%

Ankara	0.95	--	--	0.01	--	0.86	22%
Industrial sector							
Denver	0.03	0.13	--	1.98	--	2.14	9%
Minneapolis/St Paul	--	0.60	--	0.06	--	0.66	4%
Toronto	--	0.87	--	0.25	--	1.13	10%
Portland	0.17	0.54	--	0.23	--	0.94	10%
Chula Vista	--	0.31	--	0.75	--	1.06	15%
Helsinki	0.06	--	--	0.42	0.32	0.80	10%
Copenhagen	--	--	--	0.17	0.21	0.38	5%
Bologna	0.24	0.25	--	1.10	--	1.59	28%
Ankara	0.01	0.02	0.03	0.19	--	0.25	7%
Totals							
Denver	5.49	4.40	--	5.98	7.00	22.87	--
Minneapolis/St Paul	7.10	3.90	--	6.51	--	17.51	--
Toronto	2.48	5.50	--	2.97	--	10.95	--
Portland	6.91	1.32	--	0.80	--	9.03	--
Chula Vista	3.85	1.18	--	2.16	--	7.19	--
Helsinki	2.30	0.01	--	2.22	3.78	8.31	--
Copenhagen	2.48	0.22	--	1.18	3.64	7.52	--
Bologna	1.85	1.52	--	2.30	--	5.67	--
Ankara	1.63	0.04	1.24	0.92	--	3.83	--

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