



Observing human CO₂ emissions

“...conceptualizing a carbon monitoring system centered primarily on atmospheric concentration measurements, could lead to tremendous inefficiencies in the allocation of limited scientific resources, not to mention missed opportunities to provide a wider suite of decision-support information.”

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The interaction between the Earth's carbon cycle and climate change remains a top element of uncertainty within climate change projections. In order to better understand this relationship, carbon cycle scientists use a variety of modeling and observational tools to disassemble the many fluxes and reservoirs that constitute the global carbon cycle.

In addition to advancing the scientific understanding of carbon cycling, quantitative assessment of the anthropogenic portion is driven by high priority policy needs. For example, monitoring, reporting and verification the phrase used to encapsulate the emissions accounting in international climate change policy, has emerged as a critical need, not just within the international context, but also at national and local scales since these smaller governance levels enact CO₂-emissions mitigation legislation and also need to assess progress [1]. Emissions quantification can also provide information for planning as well, identifying where and when emissions occur in order to optimize mitigation strategies.

Given the convergence of science and policy needs, authoritative bodies such as the US National Research Council have recommended the construction of a science-driven carbon monitoring system (CMS) [2,3]. Such a system would combine multiple tiers of observations (e.g., ground-based, aircraft and space-based), as well as modeling elements such as ocean and terrestrial biogeochemistry models, and emission inventories, such as national reporting on fossil fuel CO₂ emissions or forest accounting [4].

The portion of the global carbon cycle attributable to the dominant anthropogenic carbon-emitting activity, fossil fuel combustion, should have particular focus

within the planned monitoring system. This is not to overlook other anthropogenic carbon emission categories (e.g., agricultural activity, deforestation or fire), but to reflect the current and future numerical dominance of the fossil carbon portion. This focus is also driven by the fact that the non-fossil portions of the carbon budget have been traditionally approached as a residual calculation and, hence, are reliant on the accuracy of fossil fuel CO₂ emissions estimation [5].

Figure 1 shows a simple schematic of how one might conceptualize the observational opportunities associated with understanding the complete causal chain leading to fossil fuel CO₂ in the atmosphere. The ultimate driver of fossil fuel CO₂ emissions is the demand for direct energy services (e.g., space heating and lighting) or energy needed to produce or deliver economic goods and services (e.g., computers, transportation and steel). The proximal driver of fossil fuel CO₂ emissions, fuel supply and demand, offers an efficient observational opportunity since fuel is a traceable, physical commodity that moves through economic ‘chokepoints’ (e.g., refineries and coal trains) but offers far less in terms of process understanding than the more wieldy upstream economic drivers. Furthermore, fuel supply and demand is not necessarily coincident with the physical location of emissions, making its connection to the downstream atmospheric observations complicated. The physical location of combustion/emissions is observationally more dispersed (e.g., an individual home), but is closer to the radiative greenhouse gas entity, CO₂ concentration, and avoids additional observational requirements, such as knowing fuel carbon contents

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or combustion efficiencies required at the fuel supply/demand point in **Figure 1**. Finally, atmospheric dispersal and concentration measurement offer the final observation point in the complete causal chain.

I would assert that the observational ‘payoff’ (accuracy and information content per dollar expended on observation) is less at either end of the causal chain but greatest in the middle at the fuel supply/demand and combustion/emissions linkages. Quantification of fossil fuel CO₂ emissions via upstream demand for economic goods and services has recently been accomplished in spite of the voluminous and wide-ranging data requirements [6]. The challenge is how to forge the connection between national-scale gross economic metrics and their transformation to CO₂ emissions at space and time scales relevant for atmospheric measurements [7,8]. From a political allocation point of view, an upstream approach is arguably a more accurate representation of responsibility for emissions as it captures the inception of fuel use. Similarly, estimation of fossil fuel CO₂ emissions via atmospheric observations is equally challenging. In this case, the accuracy and precision of CO₂ measurements is excellent, but in order to transform observations into flux estimation, knowledge about atmospheric transport is required and the latter remains scientifically challenging and uncertain at national, let alone, sub-national, scales [9, 10].

Though in the initial stages of design and agreement, the early indications are that a CMS will take an approach that focuses on the right side of **Figure 1** – what I refer to as a ‘receptor’ monitoring approach. There are a number of valid reasons for this approach. From the climate change perspective, atmospheric concentrations are the climate driver and represent a well-mixed aggregate of the complicated

emitting patterns at the planet’s surface. There is, no-doubt, a sociocultural root to emphasizing the receptor end of flux estimation; climate change science was initially driven by research in the atmospheric science community and only in recent times has there been growth in contributions from the wider research communities in ecology, sociology, economics and engineering (to name a few). Finally, and most importantly, concentration measurements have a long and productive history within the scientific community and, as such, have built up trust that is not similarly awarded to datasets collected outside of the peer-reviewed scientific process. This is particularly true of the fossil fuel emissions data, which are generally classified as ‘self-reported’ or viewed as politically driven [11]. Indeed, the receptor approach to the fossil fuel CO₂ flux estimation problem is variously described as one in which atmospheric CO₂ observations are collected in order to verify self-reported or otherwise non-scientific emission inventories [101]. To be sure, fossil fuel CO₂ inventories, such as those reported to the UN under the auspices of international climate agreements, are prey to self-reported biases, omissions and accounting errors in spite of the thorough and detailed guidance offered by the Intergovernmental Panel on Climate Change [12,13].

However, conceptualizing a carbon monitoring system centered primarily on atmospheric concentration measurements, could lead to tremendous inefficiencies in the allocation of limited scientific resources, not to mention missed opportunities to provide a wider suite of decision-support information. My research in the past few years has attempted to create an observationally based fossil fuel CO₂ emissions data product that is an alternative to the national inventories constructed through the international policy process [14]. In short,

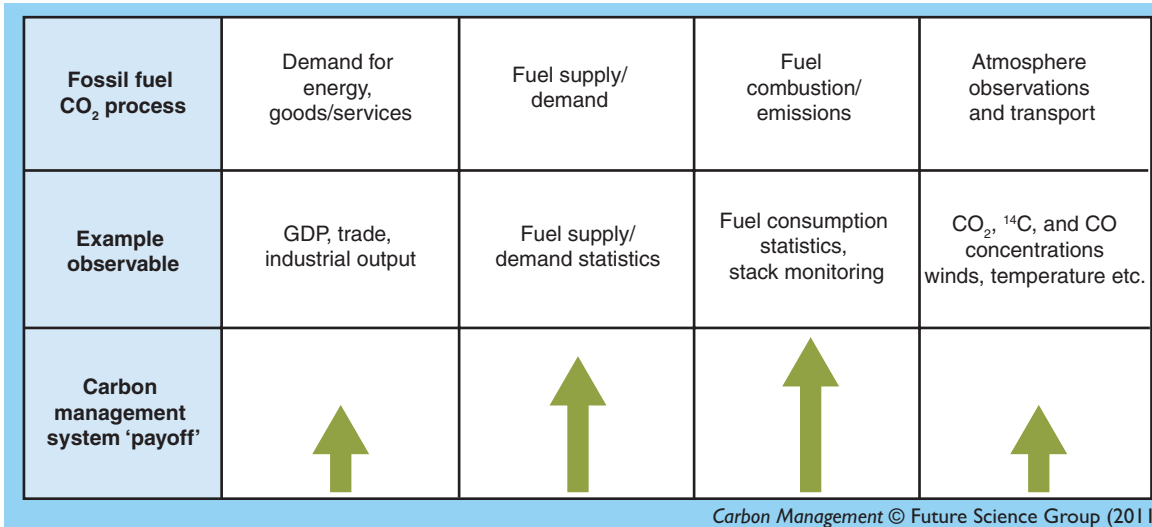
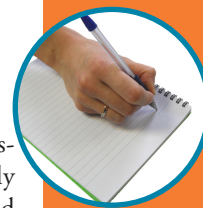


Figure 1. Fossil fuel CO₂ causal linkages.



I attempt to use scientifically based observational approaches at the high-payoff points of **Figure 1** to generate data products that are consistent with observational efforts focused on either end of **Figure 1**.

Though this work is at the early stages of development, the advantages and opportunities over the receptor approach are worth considering. Aside from the obvious advantage being the physical target of emissions monitoring/verification, direct observation of fossil fuel CO₂ emissions avoids error-prone transformation through atmospheric transport. Direct observations also come with explicit space/time detail and process information (e.g., details on fuel, combustion process, sector and economic good). This level of detail and specificity are a benefit to using the information in the planning versus verification mode. Cities, provinces and nations must prioritize allocation of resources to specific emissions mitigation activities. There is no 'one size fits all' to emission mitigation and the right choice of mitigation instrument is tied to the conditions of a location. For example, an optimal policy in a region dominated by on-road transportation emissions is not the best policy for a neighboring region in which centralized industry is prevalent. Though targets may be set at national or regional scales, the act of mitigation occurs at the scale of consumption decisions and most of these occur at buildings, road segments and industrial centers.

Direct observation of fossil fuel CO₂ emissions may also be a more economically efficient means by which to monitor and verify emissions. For example, in the US, 95% of the CO₂ emissions from fossil fuel electricity production (which accounts for almost 40% of the total US energy-related CO₂ emissions) are emitted by approximately 1500 individual facilities, all of which report fuel, energy and CO₂ emissions to the US Environmental Protection Agency [15]. Though these data do not meet the criteria of transparency and accuracy required by the scientific community, a modest investment in independent measurement and sampling at this very limited number of known facilities is potentially far more efficient and accurate than multi-tiered atmospheric concentration observations and the necessary improvement of transport algorithms. Similarly, statistics on driving and vehicular fuel consumption are not unobservable quantities. Industrial countries have record-keeping associated with fuel sales that are tracked to the retail level in many cases, not to mention the extensive traffic counting performed for a myriad of transportation planning and air quality needs.

Accomplishing direct, scientifically based observations of fossil fuel CO₂ emissions faces significant challenge. Because the production, delivery and

transformation of fossil fuels is one of the largest industries in the world, cooperation, access, and mutually beneficial exchange of information is required – and this is no small feat. Furthermore, though tractable in the nearer-term within the industrial world, the barriers, both informational and infrastructural, are larger outside of the industrial world. However, one could argue that development of accurate, science-based observations of direct emissions would be cheaper in countries that do not already have large regulatory bureaucracies currently involved in tracking and reporting for other environmental and/or economic purposes.

However, the real question is not whether this would be challenging (it would be), but rather how does the benefit:cost ratio compare to the receptor-based approach being conceptualized now for a CMS? I would propose that this has not been rigorously investigated and research is required to answer this important question. Furthermore, this should not be an either/or question. A complete CMS should build scientifically based observations at every point in **Figure 1**, and those observations should aim at internal consistency.

This would not only meet the goals of carbon monitoring and verification being discussed at the international level, but also support mitigation planning at local scales, such as in urban locations, where the optimal emissions-reducing mixture of policies lack critical information and vary dramatically from place to place. A complete CMS could also act as an independent quantification system for a carbon trading market, an eventuality that many climate policy experts consider essential to significant CO₂ emission mitigation. Like any traded commodity, price is strongly linked to trust in accurate quantification. Finally, the outreach and education opportunities should not be overlooked. Building observational information at each of the linkages in **Figure 1** offers a tremendous opportunity for improving public understanding on climate change, a necessity to building public policy.

A CMS that evolves to populate all aspects of **Figure 1**, could ultimately serve far wider economic and environmental interests. It could evolve into an energy intelligence system, something that is sorely needed given the instability of energy infrastructure in many countries. CO₂ emissions are then simply one outcome of a system that acts to quantify the energy metabolism of an economy or the life cycle of fossil carbon. Needs such as air quality, water use, and power management can be quantified far more easily, particularly in national circumstances where parallel systems already exist to track and manage these attributes.



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