clouds and precipitation, their coupling to the circulation and their role in climate sensitivity (http://www.wcrp-climate.org/index.php/gc-clouds).

The quasi-operational use of climate models in regular rounds of climate projections has strongly affected community behaviour regarding model development. Modern climate models are equivalent to well-tuned car engines. Over time, their parts have been built to neatly fit and operate well together. As a result the risk of initially degrading model performance by making substantial changes to key components is high, the time to implement ideas is long and the reward often not guaranteed. We must overcome the natural conservatism in making decisions around developing and applying new model components that has emerged through 'operational' climate models.

Ultimately though, solving what are clearly challenging but also very exciting scientific problems will require us to attract many new creative minds to work on them. This has proved difficult and people working on the fundamental issues in model development have become somewhat akin to an endangered species. It is timely then to think about dedicated activities that both improve their habitat and 'breed' the next generation. Improving the recognition of solving old model problems as a vital activity throughout the community and increasing the engagement of model developers in the broader climate science agenda are crucial. How many of the papers published in this journal alone would exist without the efforts of the modelling community? This increased recognition must go hand-in-hand with educational programmes ranging from short courses to the deeper engagement of academia in the model development enterprise, conceivably driven by an increased number of appointments of model developers in academic institutions so that the skills and excitement of being a model developer can be transferred to the next generation.

Both the climate science community and society rely on high-quality model representations of the climate system. Making climate models the best they can be at any given time should go without saying. The time to make it so is now. ❐

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COMMENTARY:

Uncertainty in projecting GHG emissions from bioenergy

Thomas Buchholz, Stephen Prisley, Gregg Marland, Charles Canham and Neil Sampson

The definition of baselines is a major step in determining the greenhouse-gas emissions of bioenergy systems. Accounting frameworks with a planning objective might require different baseline attributes and designs than those with a monitoring objective.

To evaluate the impact of any proposed greenhouse-gas (GHG) mitigation we have to be able to compare GHG emissions expected under the mitigation activity with some alternative future — typically a counterfactual baseline that reflects emissions under a 'business-as-usual' (BAU) scenario[1,2]. Defining an alternative future has been at the heart of recent controversy over the assessment of net GHG emissions associated with development and expansion of forest-based bioenergy[3–5]. Major uncertainties in the quantification of the net GHG emissions associated with forest biomass energy lie in the prediction of the baseline. The challenges inherent in predicting net GHG emissions under BAU conditions can be illustrated using the periodic assessments of the United States' forest carbon stocks from the Forest and Rangeland Renewable Resources Planning Act (RPA) assessments.

Gillenwater[6] defined a baseline as "a prediction of the quantified amount of an input to or output from an activity resulting from the expected future behaviour of the actors proposing, and affected by, a proposed activity in the absence of one or more policy interventions, holding all other factors constant (*ceteris paribus*)". Accounting strictures consider both what information would be useful to decision-makers (relevance) and the ability of experts to make meaningful measurements (reliability)[7]. To make useful decisions we must be able to compare the path travelled with an alternate path not travelled (the baseline). If wood is not harvested for energy it will be left in the forest or harvested for some other purpose.

But at what point does a level of uncertainty rule out a baseline's usefulness? Usefulness is dictated by the question being asked, therefore emissions monitoring requires different baselines from planning efforts.

There are two fundamental approaches to baseline development: one based on the current situation or constant reference and one based on a vision of an anticipated future under BAU conditions. While the constant reference intrigues by its simplicity, it is not able to account for the 'opportunity cost' of carbon sequestration. If a forest region would have increased carbon storage over time in the absence of a new harvest, but it shows no such carbon storage increase under the project scenario, no biogenic CO_2 emissions would be reported with respect to a constant reference baseline so long as carbon storage did not decrease. This approach has been adopted by the Kyoto Protocol[8] where "the net changes in greenhouse-gas emissions measured as verifiable changes in C stocks in each commitment period, shall be used to meet the commitments…". In contrast, an anticipated future baseline would represent the expected BAU changes in carbon pools and compare actual versus expected changes.

Anticipated future baselines have been widely used in modelling approaches for measuring GHG emissions of forest management alternatives (for example, bioenergy systems, carbon offset markets). But an anticipated future baseline has one major caveat: being a forward-looking tool relying on additional assumptions beyond measureable data points (as applied with a constant reference baseline), the uncertainty associated with an anticipated future baseline increases over time. Relevant but highly uncertain variables include behavioural economics (market trends, anticipated future revenues, and so on.) or ecological factors (soil quality, rainfall patterns, natural disturbances, climate change).

Most importantly, baselines depend on the framework and policy question they are designed for[9]. Policy planning efforts might call for the development of multiple scenarios to explore different pathways and to gauge sensitivities of future pathways to a range of input variables. Meanwhile, program-monitoring efforts might depend on a different set of criteria to define useful baselines, and data accuracy might become more important than completeness. Accuracy might be essential to ensure stakeholder consensus and support as well as a legally defensible foundation that centres on a scientific consensus.

The US Environmental Protection Agency is currently developing an 'Accounting Framework for Biogenic CO_2 Emissions from Stationary Sources'[5]. This framework, if adopted as a basis for a legally binding rule, would set an example by accounting for biogenic emissions rather than assuming GHG neutrality for biomass. The choice of a baseline has been at the core of this challenge.

Recent high-impact studies on GHG implications of bioenergy derived from existing forests apply one of several baselines while at the same time refraining from discussing baseline alternatives for biogenic GHG emissions. A multitude of studies apply forest growth models to compare a BAU scenario with a scenario considering additional harvests for energy[3,4,10–13], while others use forest growth projections plus a demand-side-driven increase in supply[14]. All of the studies cited above ask "How do we evaluate whether a mitigation activity is worth undertaking"[15] as part of a planning effort. Studies that assess the consequences of alternate baselines, however, are rare, and there is only a very limited literature devoted to the development of general principles to guide selection of suitable baselines[6,16–18].

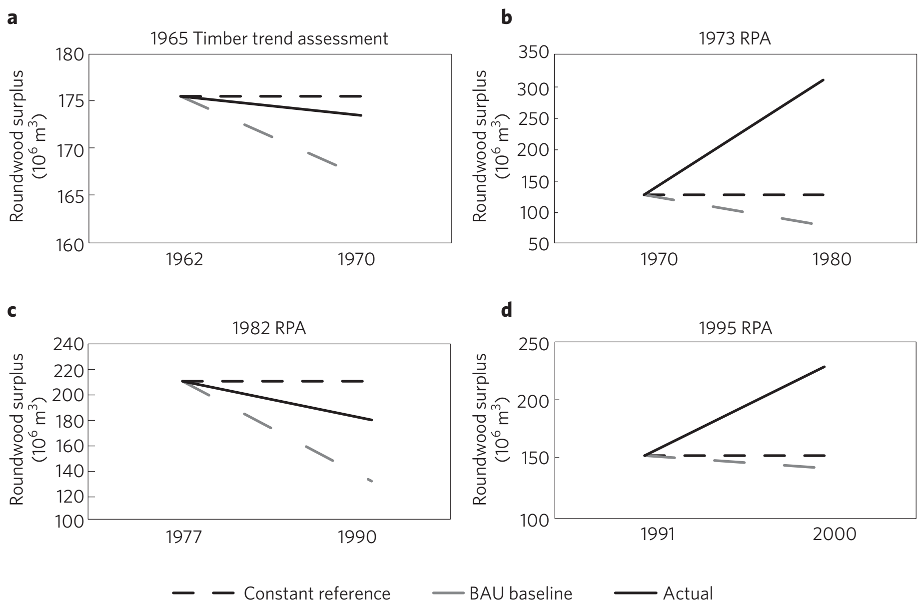

Figure 1 | Suitability of baselines in US timber trend projections. **a–d**, Comparing projected and measured baselines for roundwood surplus (growth minus mortality and removals) for the US Resources Planning Act and precursory timber trend assessments in 1965 (**a**), 1973 (**b**), 1982 (**c**) and 1995 (**d**). A constant reference baseline approach assuming constant levels of annual growth and removals would have been closer to observed actual data for every assessment since 1965 compared with an anticipated future or BAU baseline approach.

Case study

Since 1965, the US Forest Service is required approximately every decade to report projections of trends in growth, harvests, and inventory of forests nationwide. These timber trend assessments (labelled RPA assessments since 1973) involve a wide range of disciplines, including resource specialists, biometricians and economists, and rely heavily on nationwide forest inventory data from the US Forest Inventory and Analysis (FIA) program. It is instructive to compare the projections generated for each assessment with the actual data, as a way of assessing the strengths and limitations of both constant reference and anticipated future baselines.

Each RPA assessment usually begins with a point in time for which FIA has assembled the most current data. If the assessments were made using a constant reference, this starting point would be the baseline. From there, scientists use projections of economic conditions, land-use changes, resource trends, growth models and so on, to model forest harvests and inventory. Their projections usually span 40 to 50 years. If the RPA evaluations used an anticipated future approach, this projection would be the baseline.

Of perhaps the most interest to determining whether bioenergy systems would result in declining forest carbon stocks would be the 'surplus' of net forest growth, that is, gross growth minus natural mortality over harvests, land clearings and so on. Past RPA projections can be compared with what the FIA actually measured after the fact, thereby finding which baseline approach tended to best anticipate reality.

Figure 1 shows data derived from the 1965 to 1995 timber trend assessments and from FIA measurements 8 to 13 years later. A constant reference baseline is indicated by the black dashed line. For example, in Fig. 1b the constant reference shows the 1970 surplus level of about 128 million cubic metres of roundwood, that is, wood from logs. Next, the nearest-term RPA projection is for 1980; a ten-year projection. The change in projected surplus is indicated by the grey dashed line. Finally, the solid black line shows the actual surplus as measured by FIA after 1980. The difference between what RPA projected the surplus to be in 1980 (79 million cubic metres) and what it actually was (311 million cubic metres) amounted to 232 million cubic metres.

Results for all other timber trend assessments (1965, 1982, 1995; Fig. 1a,c,d, respectively) show similar trends: never in 30 years of timber trend assessments have the near-term anticipated future projections of surplus roundwood been as accurate as the constant reference would have been. Reasons for this discrepancy vary and are the subject of ongoing study. But it is hard to have tremendous confidence in our ability as scientists to accurately project the complex dynamics of forest growth, wood use, harvest, land-use change, management intensity, forest policy, disturbance, and other factors influencing surplus growth, even at relatively short (<10 years) time periods and even on a national basis. Longer projections and smaller regions should be expected to lead to even higher variability. Summarizing Fig. 1 from a decision-maker's perspective: (1) in every case the projection was that the surplus would decline, (2) in every case the surplus at the end was larger than anticipated, (3) in two of the four time periods the roundwood surplus at the end was larger than at the beginning, and (4) in all time periods the anticipated future projections were a poor indication of the ensuing reality.

The RPA assessments are not free of policy influence or intentional bias. Over-projection of biomass supply could have more negative socioeconomic consequences than under-projecting supply, therefore incentivizing assumptions and parameters towards over-projecting removals and under-projecting growth. Nevertheless, the sheer magnitude of the mismatch between predicted and measured surplus is a reminder of the bounds of science-based forecasts — even over relatively short time horizons.

Attributes

Given the poor record of projecting a BAU trend for growth of US forests, it is paramount to consider the context and the uncertainty when baselines are being developed. Gustavsson *et al.*[18] identify four principles that suggest that baselines should be accurate, comprehensive and conservative, as well as balanced against practicability. Accuracy refers to capturing data uncertainty in a spatial and temporal context. Comprehensiveness refers to data completeness ("Are all carbon pools and fluxes accounted for?") and completeness of GHG emission drivers (socio-economic and ecological), while conservativeness captures a framework's ability to not overestimate the deviation of a given GHG emission pathway from the baseline. Practicability refers to being simple enough to be widely implemented.

These attributes might receive different weightings depending on the accounting framework's purpose. If a planning framework is being developed, comprehensiveness and conservativeness might be paramount. If a monitoring framework is being developed, accuracy and practicability might receive increased scrutiny. An anticipated future baseline might be warranted if there is confidence in predicting future pathways and identifying all relevant carbon pools and drivers. However, effects of bounded rationality prevail during predictions, where modellers use simplified heuristics to reach satisfactory, rather than optimal solutions due to time, information and cognitive constraints[6]. A constant reference approach might be preferable if uncertainty in GHG emission drivers, carbon pools and fluxes prevails and practicability is considered crucial. Considering conservativeness, both baseline approaches might require frequent updates when applied in a monitoring framework (for example, Kyoto Protocol). For an anticipated future-based framework, it might be preferable to consider several rather than one baseline. Independent of baseline choices, compliance periods for monitoring frameworks might need to be short enough to reflect reality while at the same time long enough to fully capture trends.

Implications

Ultimately, baseline choice is pivotal when designing GHG emission frameworks and when evaluating GHG emissions trends. Selecting appropriate baselines depends on the policy or program goal, in particular whether the baseline will be used as a planning/scenario evaluation tool or whether it will be implemented in a regulatory scheme with potential legal implications. Given the challenges in predicting the future status of forest resources, anticipated future baselines might be best suited for planning and policy development, while constant reference baselines might be more appropriate for monitoring and regulatory frameworks. ❐

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