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Assessing Uncertainty in Bottom-up Full Carbon Accounting for Russia

Brief Project Report

1. Information on the Development of the Research Work

➢ *Overall scientific concept and goals.*

Inversions place a substantial terrestrial carbon sink in the northern hemisphere. However, the longitudinal partitioning of the terrestrial carbon sink in the northern extratropical belt (NEB: 30–90ºN) between North America, Europe and Northern Asia still exhibits large uncertainties (Denman *et al.*, 2007: Section 7.3.2.2). Our research addresses the need to close the gap between bottom-up and top-down accounting of net atmospheric carbon emissions following a so-called 'bottom-up' approach.

The thematic focus is on the consistent assessment of inventory and model data from an uncertainty point of view. The geographical focus is on Russia (1) because of the important role of Russia's terrestrial biosphere in the global carbon cycle and (2) to complement similar work executed for other regions in the NEB (*North American Carbon Program* and *CarboEurope*), thus allowing to achieve a consistent and complete bottom-up/top-down carbon flux coverage. Last but not least, (3) Russia is one signatory state to the Kyoto Protocol (KP) that is large enough to be analyzed today in a bottom-up/top-down budgeting exercise. This, in turn, allows to eventually scrutinize Russia's net emission changes under the KP in accordance with, not independent of, such a bottom-up/top-down reference framework. We resolve Russia's atmospheric CO_2-C balance in terms of four major land-use/cover units and eight bioclimatic zones (BCZs). CO_2-C flux balances are attributed to 1988–1992.

➢ *Did the scientific perspective change between the start and the end of the project?*

Yes. In the context of Russia's atmospheric carbon balance, Denman *et al.* (2007) refer in their Section 7.3.2.3.3 to Nilsson *et al.* (2003) and Shvidenko and Nilsson (2003). These authors (like most others) also took advantage of soil-vegetation pool changes at the Earth's surface and their combined uncertainty to decrease the uncertainty of the atmospheric net flux (reference period: 1988–1992). However, this is not correct as long as we still puzzle over the accounting gap, but also not from a science-theoretical point of view because the atmosphere only 'sees' the greater (combined) uncertainty that underlies total fluxes up and down—and not the smaller uncertainty that underlies pool changes at the Earth's surface.

- *If so, what form did the change take and what effect did it have on the work?*

We only report and hand over to the top-down community the combined uncertainty that directly refers to the (vertical) atmospheric net flux.

2. Most Important Results and Brief Description of Their Significance (Main Points) with Regard to

- *Most important result with regard to: Disciplinary progress.*

Our research addresses the need to close the gap between bottom-up and top-down accounting of net atmospheric carbon emissions following a so-called 'bottom-up' approach based on inventory and model data. We spotlight on Russia for the three reasons given above. The focus is on Russia's CO_2-C fluxes to and from the atmosphere and its combined uncertainty. It is this direct flux-related knowledge that is relevant for estimating Russia's atmospheric balance. However, we make use of the overall change in its soil and vegetation pools (to the extent known) to check the plausibility, not validity, of our net flux estimate. We resolve Russia's atmospheric CO_2-C balance in terms of four major land-use/cover types (arable land, forests, grasses & shrubs, and wetlands) and eight BCZs (Figure 1). Here, we report results for BCZs because of their greater relevance for a subsequent top-down exercise.

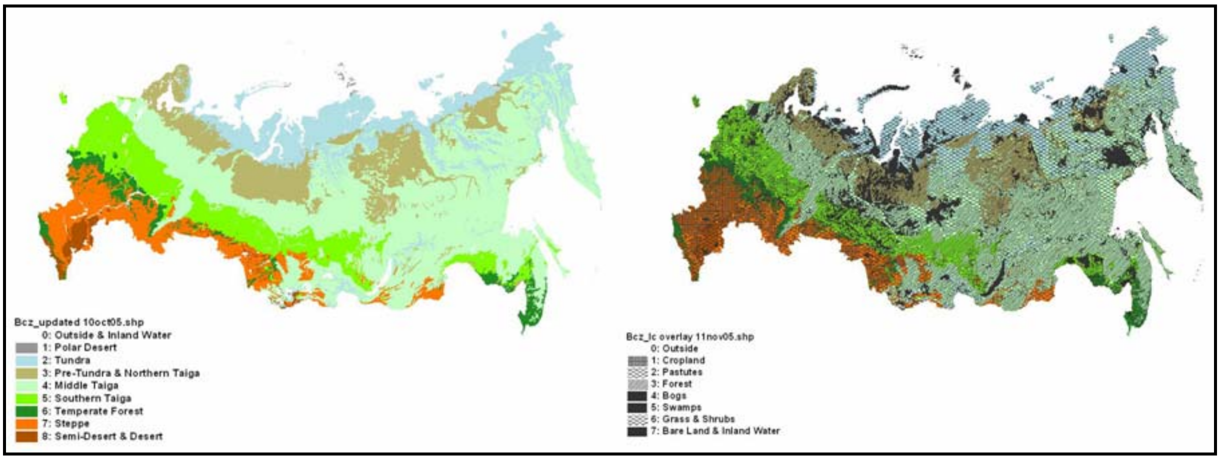

Figure 1: Russia resolved in terms of eight BCZs (left) and four major land-use/cover types (right).

For the whole of Russia during 1988–1992 we derive an atmospheric loss or net flux to Russia's terrestrial biosphere (uptake) of about 957 Tg C/yr with an uncertainty in the order of 956 Tg C/yr or 100% (90% CI; see Figure 2). The uncertainty becomes considerably greater for individual BCZs, notably for BCZs (with the exception of tundra) that behave contrary and result in a net flux to the atmosphere (Table 1). Russia's overall terrestrial sink strength turns out smaller (about 813 Tg C/yr) and its relative uncertainty somewhat greater (about 907 Tg C/yr or 112%) if resolved by land-use/cover (not shown here). While this difference can be explained, it falls beyond skillful resolution as it is outmatched by total uncertainty. Nonetheless, we are confident that we grasp the total uncertainty of Russia's terrestrial sink strength in the right order of magnitude (i.e., 907–956 Tg C/yr) and that it falls into the relative uncertainty class of 80–120% for the period 1988–1992.

Table 1: Atmospheric CO_2-C balance for Russia attributed to 1988-1992 in Tg C/yr including uncertainties (90% CI). The national soil-vegetation pool change estimate is a first-order estimate only.

Russia: BCZ Approach		Units	NPP	HR	Dis + Con	Δ(Soil+Veg) C	Atm. Balance
Polar Desert	Mean	10^6 t C/yr	0.0	0.0	0.00		**0.0**
	U90a or U90	10^6 t C/yr	0.0	0.0	0.00		**0.0**
	R_U90a or R_U90	%					
	Min	10^6 t C/yr					
	Max	10^6 t C/yr					
Tundra	Mean	10^6 t C/yr	351	236	19		**-96**
	U90a or U90	10^6 t C/yr	143	140	7		**200**
	R_U90a or R_U90	%	41	59	38		**209**
	Min	10^6 t C/yr	208	96	12		**-295**
	Max	10^6 t C/yr	493	375	27		**104**
Pre-Tundra & Northern Taiga	Mean	10^6 t C/yr	533	252	65		**-215**
	U90a or U90	10^6 t C/yr	119	149	25		**192**
	R_U90a or R_U90	%	22	59	39		**89**
	Min	10^6 t C/yr	414	103	40		**-408**
	Max	10^6 t C/yr	652	401	90		**-23**
Middle Taiga	Mean	10^6 t C/yr	2101	1063	145		**-893**
	U90a or U90	10^6 t C/yr	499	577	36		**764**
	R_U90a or R_U90	%	24	54	25		**86**
	Min	10^6 t C/yr	1602	486	109		**-1657**
	Max	10^6 t C/yr	2599	1640	180		**-129**
Southern Taiga	Mean	10^6 t C/yr	737	611	253		**127**
	U90a or U90	10^6 t C/yr	191	136	49		**239**
	R_U90a or R_U90	%	26	22	19		**188**
	Min	10^6 t C/yr	546	475	204		**-112**
	Max	10^6 t C/yr	927	747	302		**367**
Temperate Forest	Mean	10^6 t C/yr	233	188	113		**68**
	U90a or U90	10^6 t C/yr	61	38	48		**86**
	R_U90a or R_U90	%	26	20	42		**127**
	Min	10^6 t C/yr	172	150	65		**-18**
	Max	10^6 t C/yr	293	225	161		**154**
Steppe	Mean	10^6 t C/yr	592	523	176		**106**
	U90a or U90	10^6 t C/yr	195	114	33		**228**
	R_U90a or R_U90	%	33	22	19		**214**
	Min	10^6 t C/yr	398	409	143		**-121**
	Max	10^6 t C/yr	787	636	209		**334**
Semi-Desert & Desert	Mean	10^6 t C/yr	116	48	13		**-55**
	U90a or U90	10^6 t C/yr	52	29	4		**60**
	R_U90a or R_U90	%	45	60	29		**108**
	Min	10^6 t C/yr	64	19	9		**-115**
	Max	10^6 t C/yr	168	76	17		**5**

Table 1 continued.

Total	Mean	10^6 t C/yr	4662	2920	785		**-957**
	U90a or U90	10^6 t C/yr	648	687	150		**956**
	R_U90a or R_U90	%	14	24	19		**100**
	Min	10^6 t C/yr	4014	2233	635	1291	**-1913**
	Max	10^6 t C/yr	5310	3607	935	1358	**-1**

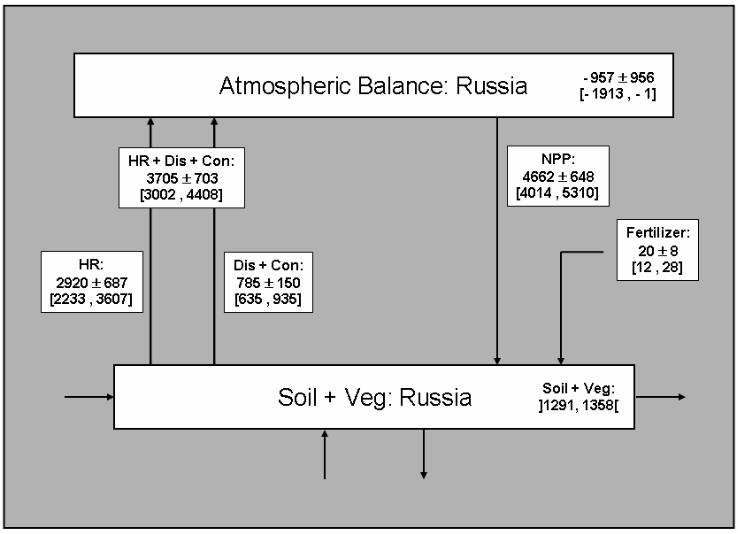

Figure 2: Figure to Table 1.

Our terrestrial sink strength and its relative uncertainty deviate considerably from 351 ± 176 Tg C/yr (90% CI) that Nilsson *et al.* (2003: Fig. 1) report with reference to their earlier study (Nilsson *et al.*, 2000). The reasons for this deviation range from a more rigorous treatment in view of limited data to the elimination of biases and shortcomings in calculations to an improved understanding of underground carbon cycling to considering also model generated data (where appropriate).

- *Most important result with regard to: Revision of the scientific state of the art.*

We conclude that the bottom-up picture for northern Asia given in Section 7.3.2.3 by Denman *et al.* (2007) appears less optimistic. Figure 7.7 in this section shows a sink strength for northern Asia of about 400 ± 350 Tg C/yr (presumedly 68% CI) while making reference to Nilsson *et al.* (2003) and Shvidenko and Nilsson (2003) in the case of Russia, to Fang *et al.* (2001) in the case of China, and to Goodale *et al.* (2002) in the case of other countries. Nilsson *et al.* (2003: Fig. 1) report a mean uptake of about 351 ± 176 Tg C/yr (90% CI) by Russia's terrestrial biosphere during the period 1988–1992, to which Russia's forest ecosystems contribute about 302 ± 144 Tg C/yr (90% CI) according to Shvidenko and Nilsson (2003: Fig. 2, Tab. 7); while Fang *et al.* (2001: Tab.2) report an accumulation rate of about 35 Tg C/yr for China's forest during 1989–1993 and Goodale *et al.* (2002) a similar rate of about 40 Tg C/yr for other countries during the late 1980s/early 1990s.[1]

[1] The other countries' sink strength is taken from House *et al.* (2003: Tab. 3), refers to living forests only, and comprises the Baltic states and CIS other than Russia.

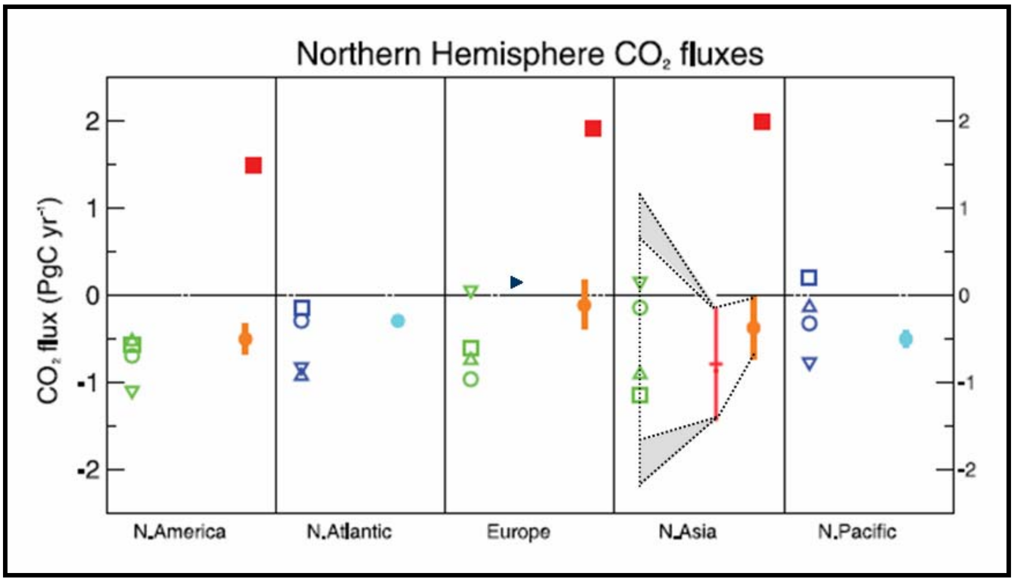

Figure 3: Regional ocean-atmosphere and land-atmosphere CO_2 fluxes for the northern hemisphere from inversion ensembles and bottom-up studies. Fluxes to the atmosphere: positive; uptake: negative. Inversion results correspond to the post-Pinatubo period 1992–1996. In the focus here: Northern Asia. Orange line: bottom-up terrestrial fluxes from Shvidenko and Nilsson (2003) for Asian Russia and Fang *et al.* (2001) for China. Green symbols: terrestrial fluxes from inversion (Gurney *et al.*, 2002, 2003; Peylin *et al.*, 2005; Rödenbeck *et al.*, 2003); their errors range between 0.5 and 1.0 Gt C yr^{-1}. Red square: fossil fuel emissions. Source: Denman *et al.* (2007: Fig. 7.7), modified. Additionally entered: Red line—our revised bottom-up net flux estimate (uptake) for entire Russia (68% CI) expanded by Fang *et al.'s* net flux estimate (uptake) for China; grey-shaded triangles—to facilitate better comparison of this expanded bottom-up net flux estimate with the aforementioned inversion estimates, with and without considering their errors.

In view of these numbers, our results for Russia suggest that Figure 7.7 in Denman *et al.* (2007) should be revised. The 1990 terrestrial sink strength for northern Asia appears to be (at least) somewhat greater than the one that we report for Russia (813–957 Tg C/yr) and to exhibit an uncertainty (at least) slightly greater than 551–581 Tg C/yr (68% CI) (equal to 907–956 Tg C/yr for a CI of 90%). In contrast to before, this greater uncertainty range would then almost embrace the range of terrestrial sink strengths derived for northern Asia via atmospheric inversion that are also shown in Figure 7.7. However, this changes if uncertainty (considering precision and within-ensemble errors) is assigned to these top-down net flux estimates (see Figure 3). This is supported by a compilation of ensembles of more recent inversion experiments for the period 1996–2001/02 (P. Ciais, 2007: pers comm.).[2] Their uncertainty intervals *in toto* seem to indicate that a best estimate or average uncertainty estimate (not yet provided by the top-down community) turns out greater than our bottom-up uncertainty, with a considerable overlap between the two. To conclude, we find a less optimistic, although more realistic, bottom-up versus top-down match for northern Asia than the IPCC authors.

➢ *Most important result with regard to: Development of hypotheses.*

What is the added value of combining full carbon accounts bottom-up and top-down? This question remained and remains subject to thorough research as each approach

[2] This personal communication provides uncertainty information to Fig. 7.7 in Denman *et al.* (2007) based on Gurney *et al.* (2002, 2003), Peylin *et al.* (2005) and Rödenbeck *et al.* (2003).

carries considerable uncertainties. A cyclo-stationary experiment carried out in 2005 with atmospheric inversion experts at LSCE (Le Laboratoire des Sciences du Climat et l'Environnement) showed that an added value seems to indeed exist. Using Russia's initially reported terrestrial sink strength uncertainty of 176 Tg C/yr (90% CI) as a-priori constraint results in a considerable *posteriori* error reduction over Russia, while the already considerable posteriori error reductions over other regions in the NEB remain almost unaffected.[3] Our interpretation of this experiment was that, after constraining Russia, the network of measurement sites used in the inverse modeling seems to become sufficiently dense over the NEB to eventually put the KP into a rigorous bottom-up/top-down uncertainty and verification context (continental view).

Nonetheless, a renewed bottom-up/top-down linking exercise with LSCE in 2007 based on our less optimistic, though more realistic, bottom-up uncertainty for Russia presented above in the context of northern Asia showed that our initial interpretation requires balancing. Using a 12 and 77-station network as representative for ~1988 and ~2000 (Rayner *et al.*, 1999, 2007) exhibits that our bottom-up uncertainty remains the main control for the *posteriori* error reduction over Russia. That is, an increased need for atmospheric measurements over Russia continues to exist.[4]

- *Most important result with regard to: Development of new/changed scientific perspective.*

We argue in favour of a conservative uncertainty approach that only hands over to the atmosphere the greater uncertainty that underlies total fluxes up and down—and not the smaller uncertainty that underlies pool changes at the Earth's surface. This opposes current practice, typically justified by "an uncertainty greater than 100% for the atmospheric net flux means that scientific progress is zero and we cannot say anything". We disagree for two reasons: 1) Our approach complies with science theory. The atmosphere only 'sees' the uncertainty that is directly associated with the vertical fluxes into and out of the atmosphere. The total net flux resulting from pool changes at the Earth's surface cannot be used for validating or verifying the atmospheric net flux. It only satisfies the criterion of plausibility. 2) An uncertainty greater than 100% for the atmospheric flux is informative. But it must be interpreted on the basis of risk.

- *Most important results with regard to: Relevance for other areas of science.*

Our research is relevant for atmospheric inversion scientists and inventory practitioners under the KP: (1) Merging bottom-up and top-down accounting continues to exhibit a comparative advantage, although involving greater uncertainties as initially conceived. (2) Scientists can be expected to consistently account CO_2 bottom-up/top-down at the scale of continents in less than ten years from now (fossil fuel CO_2 most likely sooner than terrestrial CO_2) and to even disaggregate emission changes on a country scale. That is, politically driven (mis-) accounting reported bottom-up annually under 'post-Kyoto' can be instantaneously corrected.

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[3] Note that the greater-than-required net flux uncertainty referring to a CI of 90%, not yet 68%, was used for conservative reasons as it exhibits more clearly the potential of a bottom-up/top-down linking exercise under increased uncertainty conditions.

[4] This has been supported by another LSCE experiment resolving BCZs (P. Peylin, 2007: pers. comm.).

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Acronyms and Nomenclature

a	accuracy (considering biases to the extend known; e.g.: U90a)
BCZ	bioclimatic zone
C	carbon
CI	confidence interval (e.g.: 90%)
Con	consumption
CO_2	carbon dioxide
Dis	disturbance(s)
FWF	Austrian Science Fund
G	giga (10^9)
g	gram
HR	heterotrophic soil respiration
IIASA	International Institute for Applied Systems Analysis (Laxenburg, Austria)
KP	Kyoto Protocol
LSCE	Le Laboratoire des Sciences du Climat et l'Environnement (Gif-sur-Yvette, France)
NEB	northern extratropical belt
NPP	net primary production
P	peta (10^{15})
R	relative (e.g.: R_U)
T	tera (10^{12})
t	ton (10^6 g)
U	uncertainty
Veg	vegetation
yr	year