Progress Report: September 2011 – January 2012
Project Title: Investigating Biogeophysical-Biogeochemical Interactions in the Northern High-Latitudes using a Land Surface Model Integrating Recent Advances in Terrestrial Modeling, and Land Use Change

NASA Award No. NNX11AP85H

PI: Atul K. Jain, University of Illinois
Student: Rahul Barman, University of Illinois

The overall objective of this NASA funded project is to improve our understanding of terrestrial biogeophysical-biogeochemical interactions and feedbacks in the Northern high-latitudes, using a modeling framework which integrates many of the recent improvements in terrestrial biogeophysical-biogeochemical modeling. As part of this research, we have accomplished the following tasks that we originally proposed:

1. Major Modification Implemented in ISAM Biogeophysical-Biogeochemical Model

The current ISAM represents fully prognostic C and N cycles (Yang et al., 2009; Jain et al., 2009; Yang et al., 2010), integrated with detailed representation of terrestrial biogeophysics. Biogeophysical schemes in the ISAM have been adapted from the CLM4 (Lawrence et al., 2011), its precursor CLM3.5 (Oleson et al., 2008), and the Common Land Model (CoLM, Dai et al., 2004).

Major and important modifications implemented in ISAM that are relevant for this study are:

- **(i)** Inclusion of a deep soil column (~50 m) model for soil energy exchange and balance (Lawrence et al., 2008); corrections related to snow compaction, snow temperature profile, and snow enthalpy conservation (Lawrence et al., 2011)
- **(ii)** Effects of soil organic carbon on soil hydrological and thermal properties: as implemented in Lawrence et al., 2008 with revised effects of soil organic carbon and gravel based on the new Harmonized World Soil Database (HWSD)
- **(iii)** Wind compaction of snow, and depth hoar formulation parameterizations for the Northern high Latitudes (Schaefer et al., 2009)
- **(iv)** Revised photosynthesis concepts based on Bonan et al., 2011 (added modifications to Dai et al., 2004; Chen et al., 2010)
- **(v)** Vegetation phenology and carbon allocation parameterizations (Arora and Boer, 2005)

2. Modification of datasets

The land surface dataset was updated based on the newly available HWSD (Harmonized World Soil Database); the land cover datasets have been modified based on Meiyappan and Jain, 2012 (in press).

2.1. Land cover and Land Use Change. Existing land cover datasets overestimate global forest cover in comparison to both remotely sensed land cover estimates, and FAO based inventories (Figure 1b, and Figure 2a). A larger global forest extent is most likely to overestimate Gross Primary Production (GPP), and also have consequent impacts on the land surface carbon balance (in addition to affecting the land energy and water budget). Hence, for this study, a version of a land cover dataset with significantly reduced forest cover, as developed in Meiyappan and Jain, 2012 is used (Figure 2b).

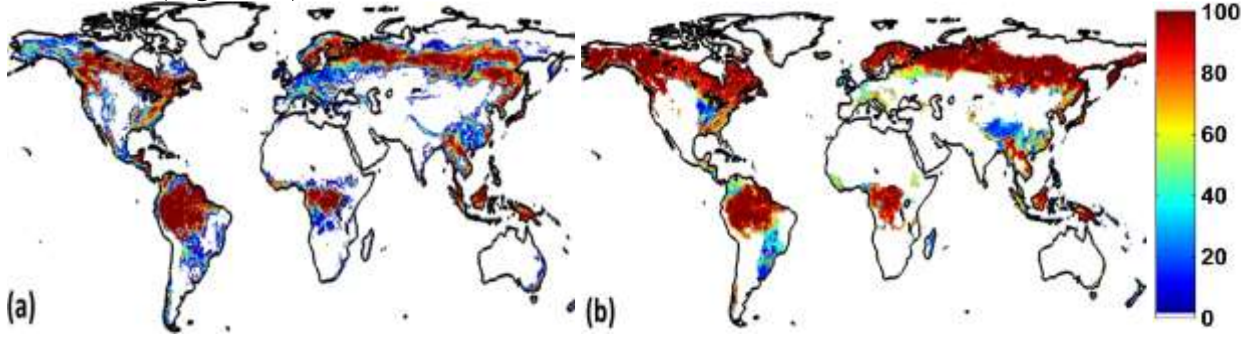


Figure 1 (from Meiyappan and Jain, 2012): Global distribution of forest area during 2005 based on (a) MODIS Land Cover Data Set and (b) estimates by Hurtt et al. (2011). Units are percentage (%) per grid cell area.

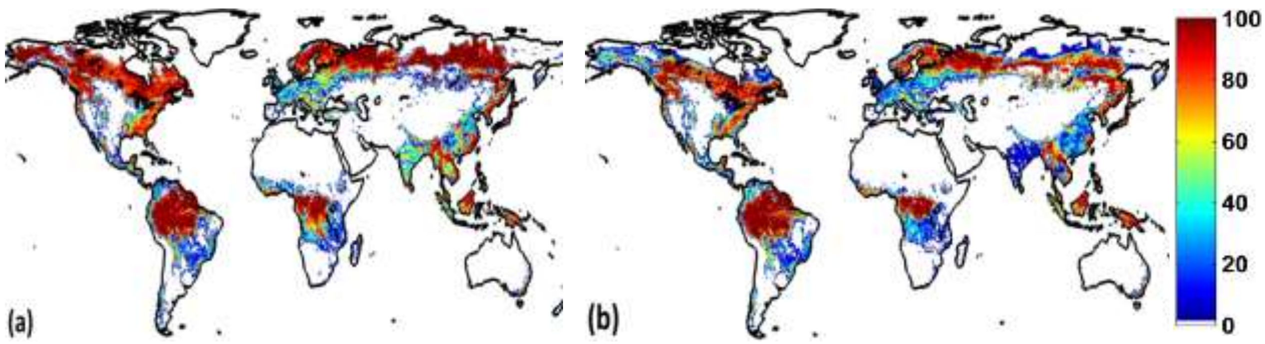


Figure 2 (from Meiyappan and Jain, 2012): Estimated global forest area for year 2005 using R&F data for cropland and pastureland, (a) Without calibration (b) After calibration using MODIS land-cover data (Friedl et al., 2010). Units are in percentage (%) per grid cell area.

Forest cover in ISAM is partitioned into primary and secondary forests (see Figure 3 for fractional primary/secondary forest cover in the year 2005).

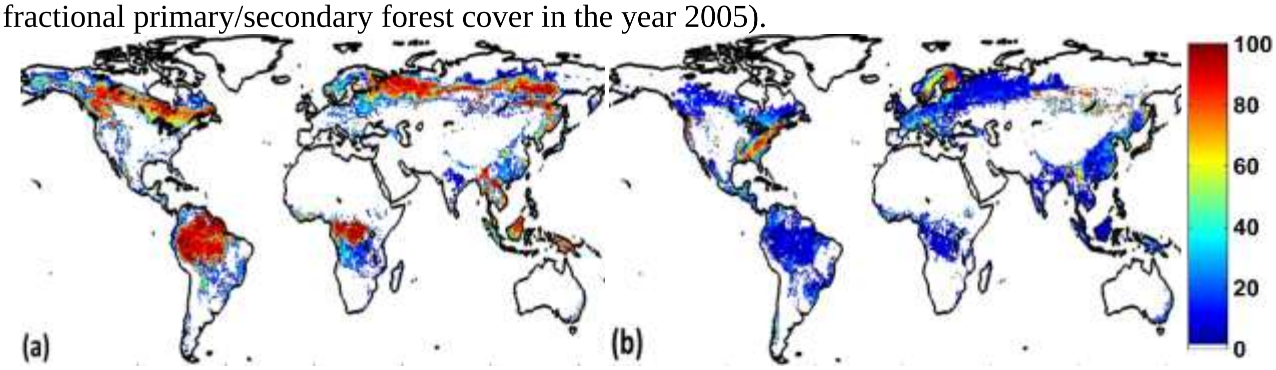
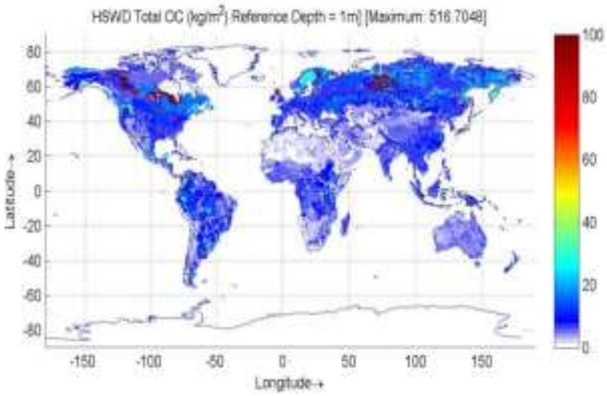
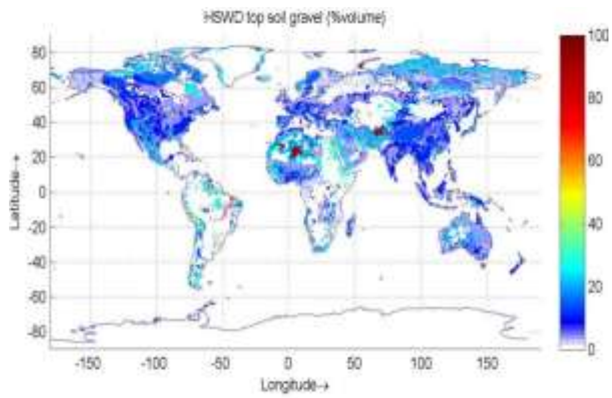


Figure 3 (from Meiyappan and Jain, 2012): Estimated (a) primary and (b) secondary forest area for the year 2005 using R&F data for cropland and pastureland. Units are in percentage (%) per grid cell area.

2.2 Soil dataset (based on the newly available HSWD): The newly available HWSD (Harmonized world Soil Database) dataset provides revised estimates of global soil organic carbon (Figure 4a), and soil gravel content (Figure 4b). These are integrated into the model and the effects of these are implemented to modify soil thermal and hydrological characteristics.



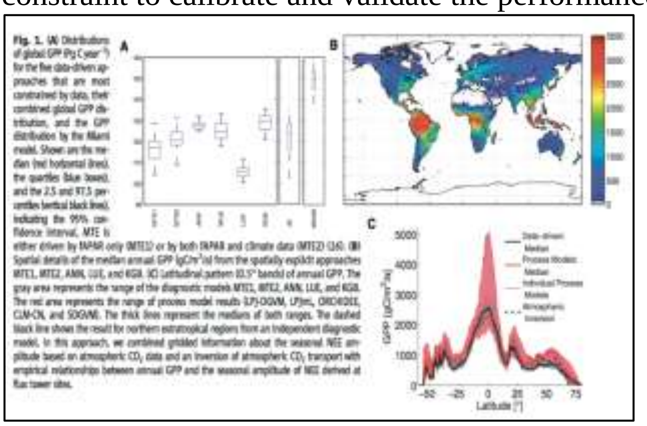


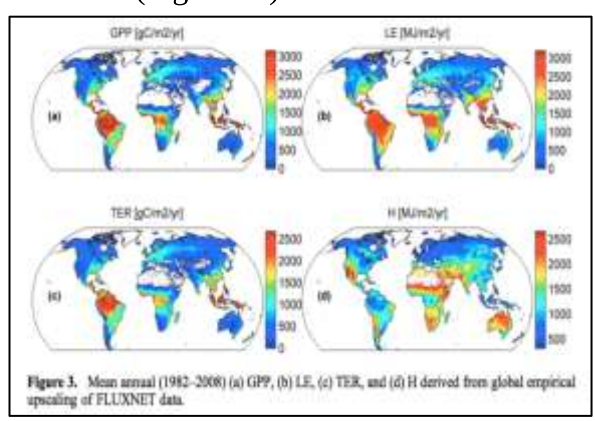
(a) (b)

Figure 4: (a) HWSD total soil organic carbon (Total ~ 516 KgC/m^2) in the top 1 m of soil; (b) HWSD top-soil gravel (% volume)

3. Results of improvement of ISAM using FLUXNET derived global, gridded products

FLUXNET derived globally gridded products of water, energy, and carbon fluxes (Beer et al., 2010; Jung et al., 2011) were used to calibrate and validate ISAM performance. Beer et al., 2010 used site-specific FLUXNET data in conjunction with various diagnostic machine learning schemes to estimate a global GPP estimate of 123+/- 8 GtC/yr (Figure 5a). For the current work, one of these datasets, the FLUXNET_MTE (Jung et al., 2011) is used as an observational constraint to calibrate and validate the performance of ISAM (Figure 5b).





(a) (b)

Figure 5: FLUXNET derived globally gridded data products – (a) From Beer et al., 2011 ensemble of machine learning schemes and comparison with existing LSMs (b) From Jung et al., 2011, the FLUXNET_MTE product for GPP, Latent Heat (LE), Sensible Heat (H), and Total Ecosystem Respiration (TER)

Jung et al., 2011 provides globally gridded monthly estimates of GPP, Latent Heat, Sensible Heat, and Total Ecosystem Respiration (not used for this current study due to high uncertainties) from 1982-2004, which are used to validate the performance of the ISAM and the recently improved CLM4a (Bonan et al., 2011)

3.1 Comparison of ISAM annual GPP with FLUXNET_MTE for 1982-2004

(i) ISAM estimated annual GPP during 1982-2004 is ~122 GtC/yr, corresponding to FLUXNET_MTE estimate of ~118 GtC/yr

(ii) $V_{cmax25}^{opt} f(N)$ values in ISAM are same as recommended by Kattage at al., 2009 for tropical/temperate forests [Tropical evergreen ~41; Tropical Deciduous ~ 58; Temperate Evergreen ~ 41; Temperate Deciduous ~ 58]. Savanna has a $V_{cmax25}^{opt} f(N)$ *of* 70 in ISAM. $V_{cmax25}^{opt} f(N)$ for ISAM forest ecosystems are in better agreement than CLM4a (Bonan et al., 2011) with Kattage et al., 2009

(iii) Much lower than recommended values are used in ISAM for Boreal ~ 30, Tundra ~ 30, Crop ~ 35; Grassland ~ 40 (Kattage at al., 2009***:*** Boreal ~ 39-62, Tundra ~ 78, Grassland ~ 78). CLM4a also has equivalent discrepancies. These discrepancies highlight the need to revisit model concepts and associated photosynthesis parameters.

3.2 Comparison of ISAM annual GPP with FLUXNET_MTE for 1982-2004

1. ISAM estimated annual Latent Heat during 1982-2004 is ~14.70 x 10^{16} J/yr, corresponding to FLUXNET_MTE estimate of ~15.69 x 10^{16} J/yr

3.3 Comparison of zonal estimates of GPP and Latent Heating amongst ISAM, FLUXNET_MTE and CLM4a

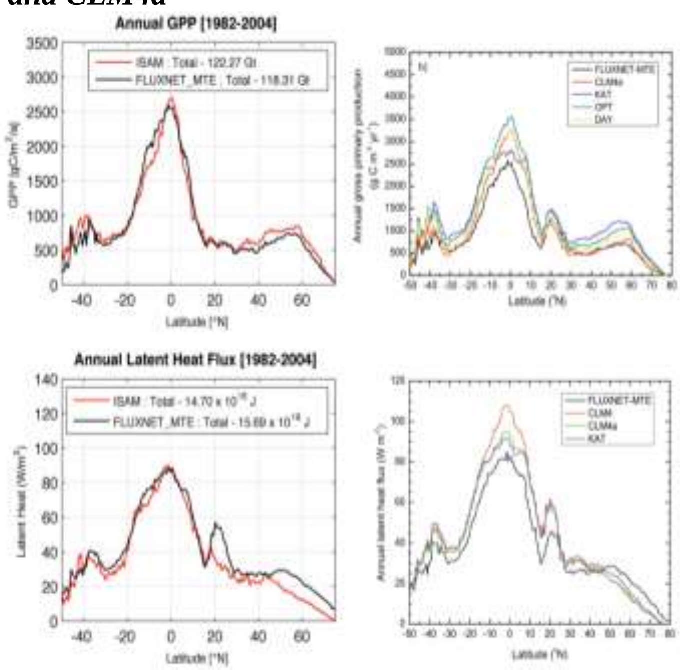


Figure 6: Comparison of zonal distributions of annual GPP and Latent Heat ISAM amongst ISAM, FLUXNET_MTE and CLM4a (Bonan et al., 2011)

- **(i)** Both models overestimate GPP in and significantly underestimate LE in the Northern High latitudes, where GPP-LE coupling do not seem to be as closely coupled (unlike other ecosystems)
- **(ii)** High concentration of soil organic carbon in the CLM4/CLM4a soil dataset, which leads to drier surface and top soil layers, resulting in reduced plant water uptake, and reduced soil-evaporation
- **(iii)** ISAM implements the new HWSD SOM dataset, with lower carbon concentration; yet the model remains biased low for Northern High Latitude ET. Currently, these limitations in ISAM are being explored.
- **(iv)** ISAM misses the ET maxima at 20^{o}N, the 2005 Land cover data used has very high crops/pastureland

3.4 Calibration of Sensible Heat in ISAM to achieve better surface energy balance

In addition to calibrating the GPP and the Latent Heat in ISAM (following the methodology in Bonan et al., 2011), the Sensible Energy component was also calibrated to achieve a much better energy balance and partitioning at the land surface in comparison to FLUXNET_MTE, as shown in Figure 7. CLM4a significantly overestimates Sensible Heat in the tropics (Not shown here).

Improved energy balance in ISAM was achieved by reduction of net radiation absorbed by canopy (consistent with FLUXNET estimates); this was obtained through modification of canopy optical properties (Reflectance, Transmittance) and through modification of Stomatal conductance & photosynthetic parameters. Prier to calibration, ISAM had very high Sensible Heat in the tropics due to high canopy absorption, leading to high Leaf Temperature → High Leaf Respiration → Low NPP/GPP ratio (Higher Net Radiation at tropics → Higher Sensible Heat → high leaf temperature, lower NPP/GPP ration due to higher leaf growth and maintenance respiration)

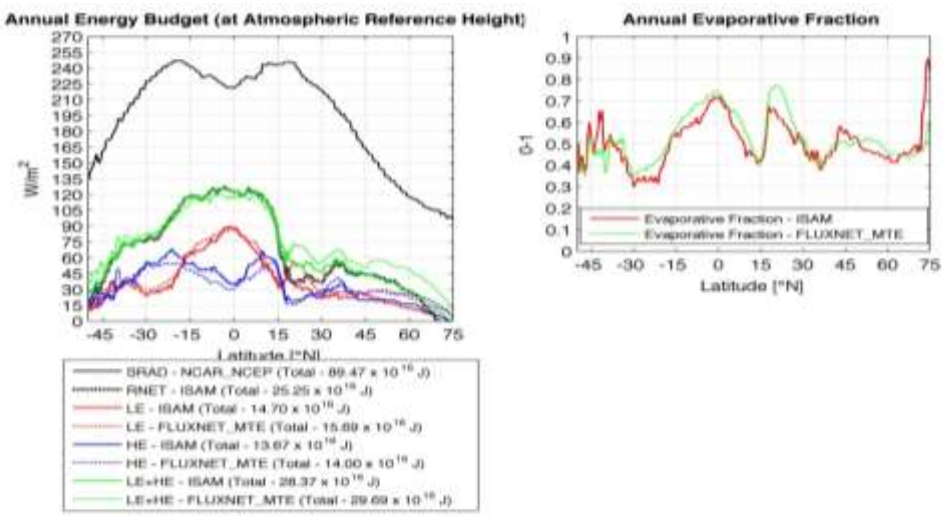


Figure 7: Comparison of zonal distributions (a) annual energy balance in ISAM vs. FLUXNET_MTE – left panel (b) Annual Evaporative Fraction – right panel

3.5 Sensitivity of GPP and NPP to model structural and parameter changes

With the inclusion of all the above model revisions, several process specific simulations were also carried out to quantify the significance of these processes/calibrations for the Northern high-latitudes. For example, figure 8 shows the sensitivity GPP and NPP to some of the newly implemented processes and schemes that specially affect the evolution of soil temperature in the high latitudes.

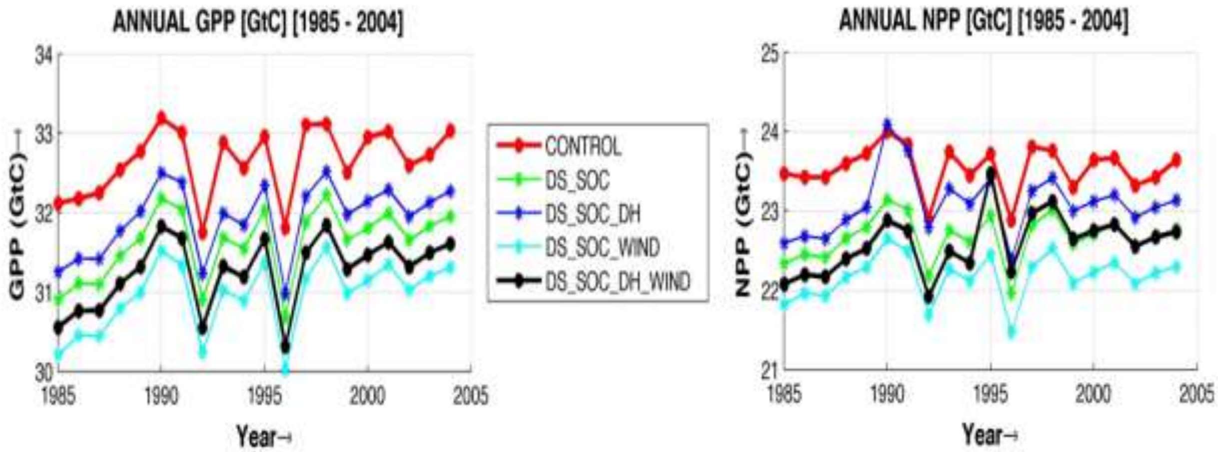


Figure 8: Sensitivities of GPP/NPP for the Northern high-latitudes for 1985-2004; experiment nomenclature: CONTROL: Original model without new improvements; DS_SOC: Control with deep soils and soil organic carbon effects; DS_SOC_DH: Adding depth hoar effects to DS_SOC; DS_SOC_WIND: Adding wind compaction of snow effects to DS_SOC; DS_SOC_DH_WIND: All improvements implemented. As shown by the figures, the GPP and NPP are significantly sensitive to soil temperature for the high latitude regions. The soil temperature in the original (CONTROL) model is the warmest. Incorporating newer effects such as deep soils, organic soils, wind compaction of snow cool the soils; the depth hoar formation has warming effects for the boreal/Taiga regions (not shown).

4. Results of soil biogeochemistry (C-N) spin-up using the improved ISAM for the Northern high-latitudes

ISAM was spun-up for 6000 calendar years to reach an approximate steady state for soil carbon and nitrogen accumulation. Figure 9 shows the global spin-up results for soil carbon and nitrogen (top panel), together with PFT specific soil carbon accumulation characteristics (bottom panel). The total global soil carbon in ISAM is approximately ~1400 GtC, consistent with several observation derived estimates (e.g., Post et al., 1982; Tarnocai et al., 2009 – observations for the circumpolar Northern Nigh latitudes; HSWD dataset. However, there may be very large uncertainties in current estimates as reported in literature). The boreal and the tundra soils in ISAM simulate maximum carbon storage, and also take the maximum time to reach a steady state (~6000 calendar years).

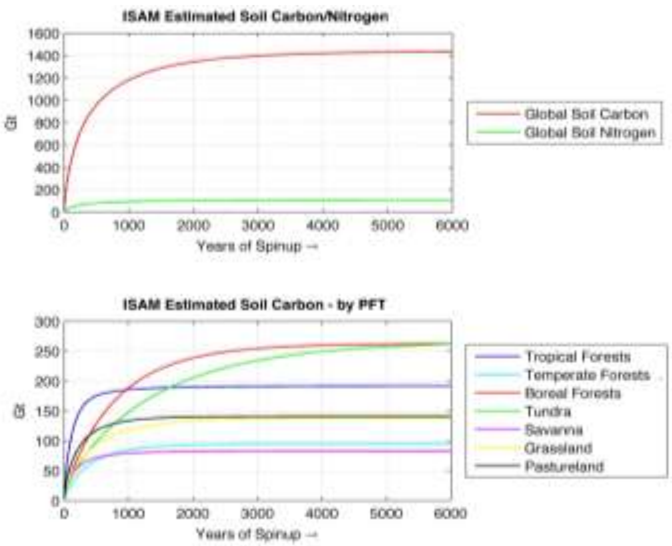


Figure 9: ISAM simulated global soil carbon and nitrogen pools after spin-up

Figure 10 shows the spatial distribution of ISAM simulated Northern High latitude carbon. The simulation shows that boreal soils may hold as much as 45 KgC/m^2, while the tundra soils may accumulate up to 70 KgC/m^2.

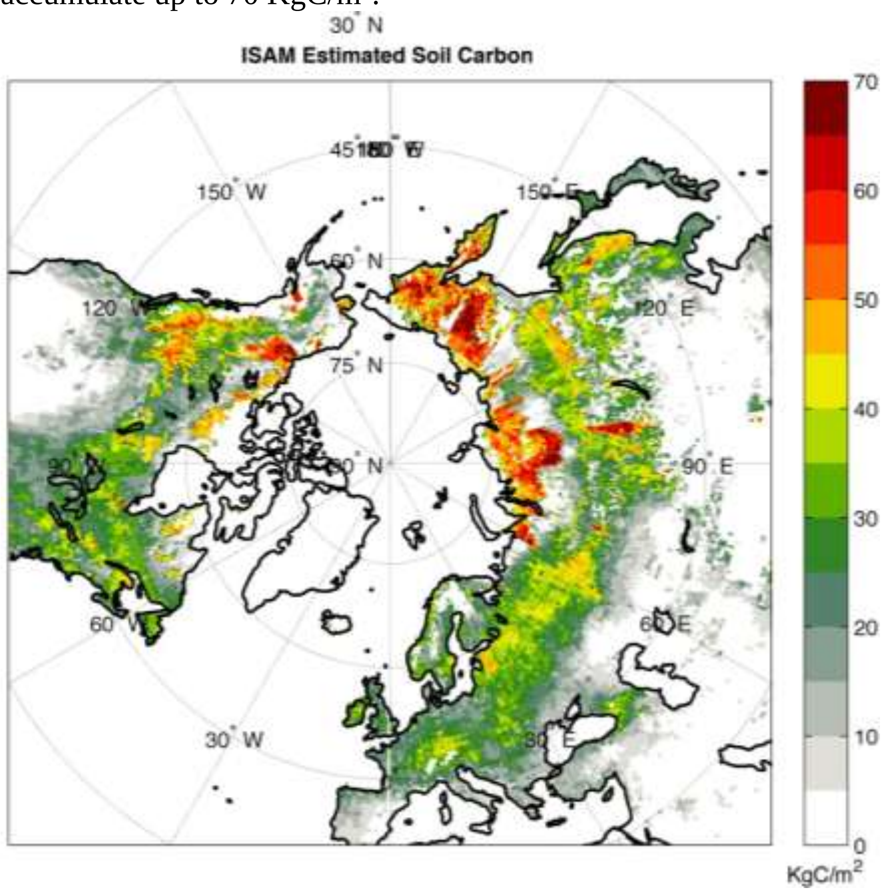


Figure 10: Spatial distribution of ISAM simulated Northern High latitude carbon (~ present day)

5.REFERENCES

Arora, V. K., & Boer, G. J. (2005). A parameterization of leaf phenology for the terrestrial ecosystem component of climate models. Global Change Biology, 11(1), 39-59.

Beer, C., et al. (2010), Terrestrial gross carbon dioxide uptake: Global distribution and covariation with climate, Science, 329, 834–838, doi:10.1126/science.1184984.

Bonan, G. B., P. J. Lawrence, K. W. Oleson, S. Levis, M. Jung, M. Reichstein, D. M. Lawrence, and S. C. Swenson (2011), Improving canopy processes in the Community Land Model version 4 (CLM4) using global flux fields empirically inferred from FLUXNET data, J. Geophys. Res., 116, G02014, doi:10.1029/2010JG001593.

Chen, H., R. E. Dickinson, Y. Dai, and L. Zhou (2010), Sensitivity of simulated terrestrial carbon assimilation and canopy transpiration to different stomatal conductance and carbon assimilation schemes, Clim. Dyn., doi:10.1007/00382-00010-00741-00382.

Dai, Y., Dickinson, R. E., & Wang, Y. P. (2004). A two-big-leaf model for canopy temperature, photosynthesis, and stomatal conductance. Journal of Climate, 17(12), 2281-2299.

Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., and Huang, X. (2010), "MODIS Collection 5 Global Land Cover: Algorithm Refinements and Characterization of New Datasets', Remote Sensing of Environment, 114, 168-182.

FAO (2010), Global Forest Resources Assessment 2010, Main Report, FAO Forestry paper 163, Rome, Italy. (Available at www.fao.org/forestry/fra/fra2010/en/).

Goldewijk, K. K. Estimating global land use change over the past 300 years: The HYDE database. Global Biogeochemical Cycles, 15(2)

Hurtt, G., Frolking, S., Fearon, M., Moore, B., Shevliakova, E., Malyshev, S., et al. (2006). The underpinnings of land-use history: Three centuries of global gridded land-use transitions, wood-harvest activity, and resulting secondary lands. Global Change Biology, 12(7), 1208-1229.

Jain, A., Yang, X., Kheshgi, H., McGuire, A. D., Post, W., & Kicklighter, D. (2009). Nitrogen attenuation of terrestrial carbon cycle response to global environmental factors.

Jung, M., M. Reichstein, and A. Bondeau (2009), Towards global empirical upscaling of FLUXNET eddy covariance observations: Validation of a model tree ensemble approach using a biosphere model, Biogeosciences, 6, 2001–2013, doi:10.5194/bg-6-2001-2009.

Kattge, J., W. Knorr, T. Raddatz, and C. Wirth (2009), Quantifying photo- synthetic capacity and its relationship to leaf nitrogen content for global- scale terrestrial biosphere models, Global Change Biol., 15, 976–991, doi:10.1111/j.1365-2486.2008.01744.x.

Lawrence, D. M., Slater, A. G., Romanovsky, V. E., & Nicolsky, D. J. (2008). Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. J.Geophys.Res, 113, F02011.

Lawrence, D. M., et al. (2011), Parameterization improvements and functional and structural advances in version 4 of the Community Land Model, J. Adv. Model. Earth Syst., 3, M03001, doi:10.1029/ 2011MS000045.

Meiyappan and Jain, Over two centuries of historical land-use/cover change and conversions: Global estimates using three different agricultural data sets, 2012

Oleson, K., Niu, G., Yang, Z., Lawrence, D., Thornton, P., Lawrence, P., et al. (2008). Improvements to the community land model and their impact on the hydrological cycle. J.Geophys.Res, 113

Post, W. M., Pastor, J., Zinke, P. J., & Stangenberger, A. G. (1985). Global patterns of soil nitrogen storage. Nature, 317(6038), 613-616.

Schaefer, K., Zhang, T., Slater, A. G., Lu, L., Etringer, A., & Baker, I. (2009). Improving simulated soil temperatures and soil freeze/thaw at high-latitude regions in the simple Biosphere/Carnegie-ames-stanford approach model. Journal of Geophysical Research, 114(F2), F02021.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G. and Zimov, S., 2009: Soil organic carbon pools in the northern circumpolar permafrost region. Global Biogeochem. Cycles 23, doi:10.1029/2008GB003327.

Yang, X., Wittig, V., Jain, A. K., & Post, W. (2009). Integration of nitrogen cycle dynamics into the integrated science assessment model for the study of terrestrial ecosystem responses to global change. Global Biogeochemical Cycles, 23(4)

Yang, X., Richardson, T., & Jain, A. (2010). Contributions of secondary forest and nitrogen dynamics to terrestrial carbon uptake. Biogeosciences Discussions, 7(2), 2739-2765.