SCIENTIFIC REPORTS

OPEN

SUBJECT AREAS:
CLIMATE CHANGE
ADAPTATION
ECOLOGY
ENVIRONMENT

Received
11 July 2011

Accepted
30 September 2011

Published
13 October 2011

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Increasing trends of soil greenhouse gas fluxes in Japanese forests from 1980 to 2009

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Forest soils are a source/sink of greenhouse gases, and have significant impacts on the budget of these terrestrial greenhouse gases. Here, we show climate-driven changes in soil GHG fluxes (CO_2 emission, CH_4 uptake, and N_2O emission) in Japanese forests from 1980 to 2009, which were estimated using a regional soil GHG model that is data-oriented. Our study reveals that the soil GHG fluxes in Japanese forests have been increasing over the past 30 years at the rate of 0.31 Tg C yr^{-2} for CO_2 (0.23 % yr^{-1}, relative to the average from 1980 to 2009), 0.40 Gg C yr^{-2} for CH_4 (0.44 % yr^{-1}), and 0.0052 Gg N yr^{-2} for N_2O (0.27 % yr^{-1}). Our estimates also show large interannual variations in soil GHG fluxes. The increasing trends and large interannual variations in soil GHG fluxes seem to substantially affect Japan's Kyoto accounting and future GHG mitigation strategies.

Forest soils play important roles in greenhouse gases (GHGs) emissions and uptake[1]. In general, forest soils work as a source of CO_2 and N_2O (from the soil surface to the atmosphere) and as a sink of CH_4 (from the atmosphere to the soil surface; upland soils). These emissions and uptake values are strongly controlled by not only soil physiochemical properties but also by environmental conditions[2–6]. An evaluation of these gas fluxes is essential at the regional scale (e.g., global or country) as well as the site scale. In particular, country-scale evaluation and prediction are very important under the United Nations Framework Convention on Climate Change.

Observations reveal that the Earth has been experiencing climate change. The global mean temperature has been steadily rising, especially in the past three decades (1980–2009) [7,8]. The rate of warming between 1956 and 2005 was 0.13 °C per decade, almost two times greater than that between 1906 and 2005 (ref. 7). Precipitation patterns are also changing: it is reported that there have been an increasing number of heavy precipitation events and that droughts have become more common[7].

These recent changes in climate should have affected global terrestrial GHG budgets; in fact, substantial evidence for this has been reported in recent studies. For instance, it is reported that the terrestrial net primary production increased globally from 1982 to 1999 because of the relaxation of several climatic constraints on plant growth[9]. However, a reduction in the global terrestrial net primary production from 2000 through 2009, which was induced by drought, has also been reported despite that decade being the warmest since 1980 (ref. 8). As in the case of plant growth, climate change likely affects the soil GHG fluxes in forests[10,11].

We estimated the climate-driven changes in soil GHG fluxes (CO_2 and N_2O fluxes from the soil surface to the atmosphere and CH_4 flux from the atmosphere to the soil surface) in Japanese forests at a 1-km resolution using a regional soil GHG model and soil gas flux submodels, which are simple data-oriented models that were data-assimilated using a Bayesian calibration.

Results

The estimated total gas fluxes for CO_2 emission, CH_4 uptake, and N_2O emission were 137.1 Tg C yr^{-1} (Monte Carlo 95 % confidence interval, 110.0–155.4 Tg C yr^{-1}; mean flux per area, 585.9 g C m^{-2} yr^{-1}), 90.5 Gg C yr^{-1} (49.1–136.0 Gg C yr^{-1}; 386.7 mg C m^{-2} yr^{-1}), and 1.94 Gg N yr^{-1} (0.70–5.21 Gg N yr^{-1}; 8.28 mg N m^{-2} yr^{-1}), respectively (Fig. 1). The N_2O flux showed the largest uncertainty, while the CO_2 gas flux showed the smallest uncertainty (grey areas in Fig. 1). Our simulations of the past 30 years estimate that the fluxes of CO_2 emission,

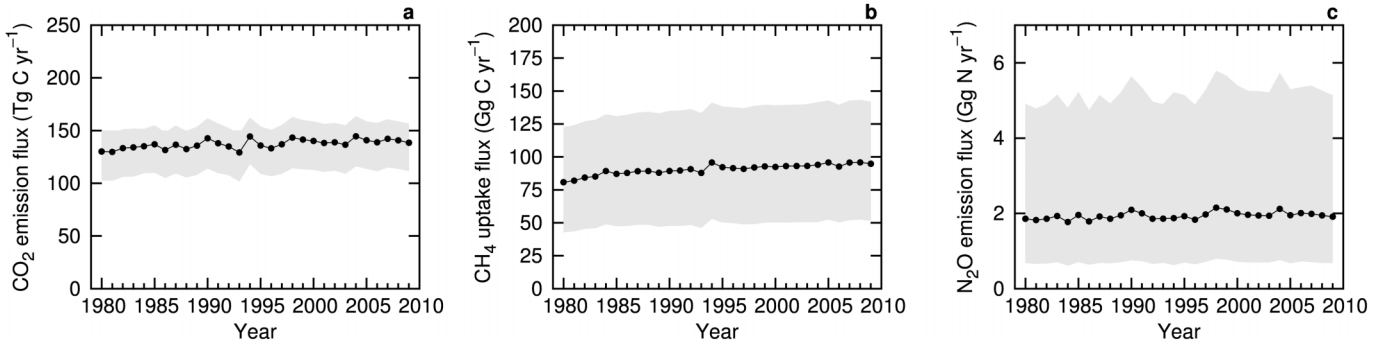

Figure 1 | Estimated soil GHG fluxes in Japan's forest soil. (a) Estimated soil CO_2 emission flux; (b) CH_4 uptake flux; (c) N_2O emission flux. The grey regions show the 95 % confidence limits of the Monte Carlo simulations (N=1000).

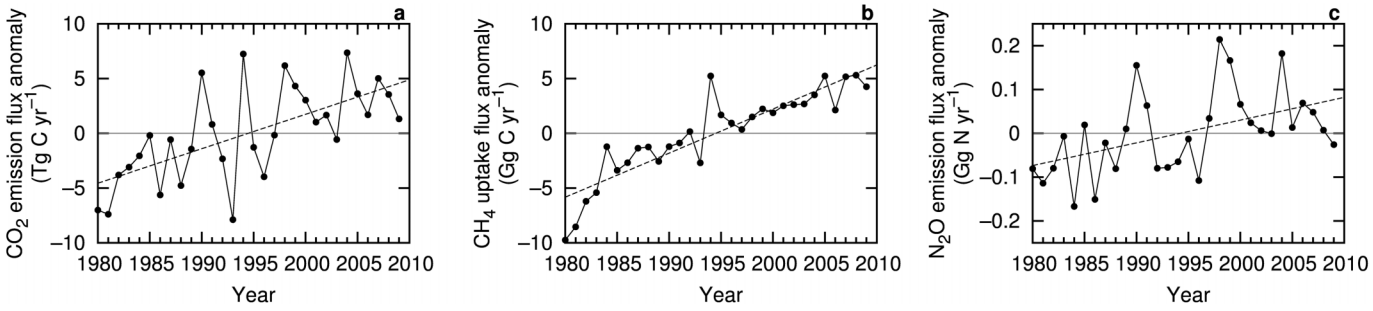

Figure 2 | Anomalies in soil GHG fluxes. (a) CO_2 emission flux anomaly (slope=0.31 Tg C yr^{-2}, P=0.0001); (b) CH_4 uptake flux anomaly (slope=0.40 Gg C yr^{-2}, P<0.0001); (c) N_2O emission flux anomaly (slope=0.0052 Gg N yr^{-2}, P=0.0071). The anomaly from the average between 1980 and 2009 is shown.

CH_4 uptake, and N_2O emission have been increasing (Fig. 2). The increasing rates for CO_2, CH_4, and N_2O were 0.31 Tg C yr^{-2} (0.23 % yr^{-1}, relative to the average from 1980 to 2009, P=0.0001), 0.40 Gg C yr^{-2} (0.44 % yr^{-1}, P<0.0001), and 0.0052 Gg N yr^{-2} (0.27 % yr^{-1}, P=0.0071), respectively. Assuming that the global warming potentials of CH_4 and N_2O are 25 and 298 times greater than that of CO_2 over a period of 100 years[7], the converted fluxes for CO_2, CH_4, and N_2O in the CO_2 equivalent were 502.9 (362.1–680.4) Tg CO_2−eq yr^{-1}, 3.02 (2.01–4.03) Tg CO_2−eq yr^{-1}, and 0.91 (0.39–1.90) Tg CO_2−eq yr^{-1}, respectively, and the budget in terms of global warming potential was 500.8 Tg CO_2−eq yr^{-1} (the sum of the CO_2 and N_2O sources and the CH_4 sink). Because of the dominant contribution of the CO_2 flux, the potential is increasing at a rate of 1.14 Tg CO_2−eq yr^{-2} (P=0.0001).

We examined the relationships between the anomalies in the gas fluxes and those in the air temperature and the precipitation. To focus on the effects of air temperature and precipitation, the effect of atmospheric CH_4 concentration was removed in this analysis for CH_4 (See Supplementary Information). When the effect of the atmospheric concentration was removed, the increasing rate for CH_4 was 0.083 Gg C yr^{-2} (0.09 % yr^{-1}, P<0.0171). As expected from the structures and parameters of the soil gas flux submodels (see Supplemental Information), the anomalies of the fluxes of CO_2 emission and N_2O emission showed clear positive correlations with that of air temperature (Fig. 3; 6.9 Tg C yr^{-1} °C^{-1}, r=0.90, P<0.0001 for CO_2; 0.14 Gg N yr^{-1} °C^{-1}, r=0.83, P<0.0001 for N_2O), whereas, although a similar positive correlation was seen, the correlation for CH_4 flux was weak and not significant (0.93 Gg C yr^{-1} °C^{-1}, r=0.31, P=0.0975). The anomalies for CH_4 and N_2O showed clear correlations with precipitation, but the trends were opposite (Fig. 4; −0.67 Gg C yr^{-1} 100 mm^{-1}, r=−0.76, P<0.0001 for CH_4; 0.029 Gg N yr^{-1} 100 mm^{-1}, r=0.57, P=0.0010 for N_2O). The anomaly for CO_2 was not correlated with that of precipitation (Fig. 4; −0.09 Tg C yr^{-1} 100 mm^{-1}, r=−0.038, P=0.8406).

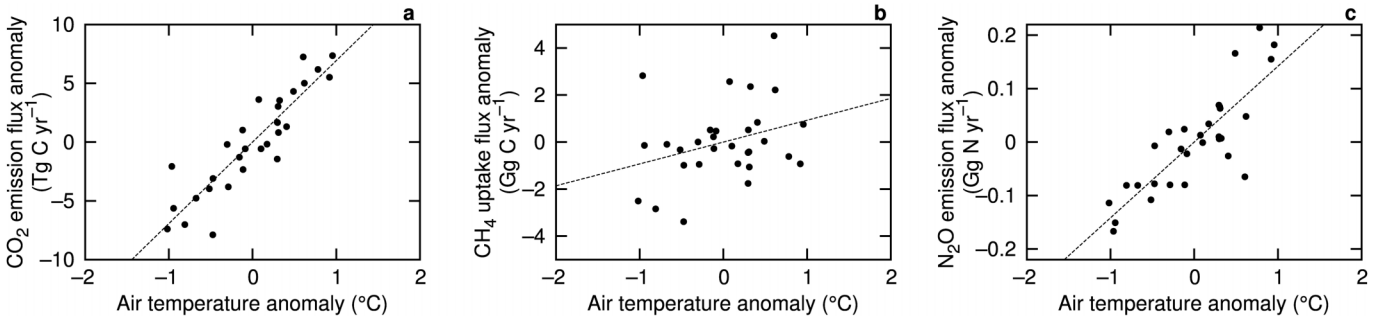

Figure 3 | Relationships between the air temperature anomaly and the soil GHG flux anomaly. (a) for the CO_2 emission flux (slope=6.9 Tg C yr^{-1} °C^{-1}, P<0.0001); (b) for the CH_4 uptake flux (slope=0.93 Gg C yr^{-1} °C^{-1}, P=0.0975); (c) for the N_2O emission flux (0.14 Gg N yr^{-1} °C^{-1}, P<0.0001). The effect of the atmospheric CH_4 concentration on CH_4 uptake was removed in this analysis. The anomaly from the average between 1980 and 2009 is shown.

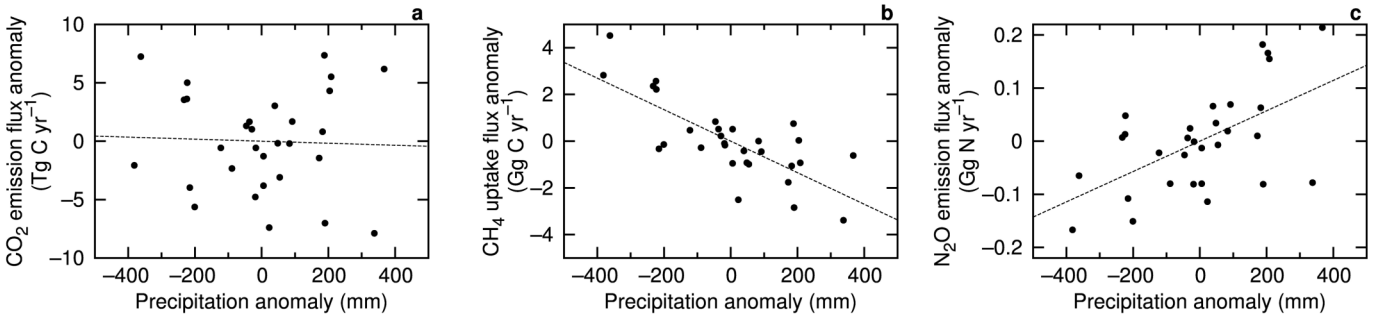

Figure 4 | Relationships between the precipitation anomaly and the soil GHG flux anomaly. (a) for the CO_2 emission flux (slope = −0.09 Tg C yr^{-1} 100 mm^{-1}, P=0.8406); (b) for the CH_4 uptake flux (slope = −0.67 Gg C yr^{-1} 100 m^{-1}, P<0.0001); (c) for the N_2O emission flux (0.029 Gg N yr^{-1} 100 mm^{-1}, P=0.0010). The effect of the atmospheric CH_4 concentration on CH_4 uptake was removed in this analysis. The anomaly from the average between 1980 and 2009 is shown.

Discussion

Similar temperature-associated increases in the soil CO_2 flux (called soil respiration) on the global scale have been reported based on a meta-analysis of a five-decade record of worldwide soil CO_2 flux data[10]. Furthermore, our estimate of the response of the soil CO_2 flux to the air temperature, a Q_{10} (the factor by which the flux increases when the temperature is increased by 10 °C) of 1.66, agrees well with the result from the meta-analysis (Q_{10}=1.5).

Assuming that the same increasing trends continue, the fluxes of CO_2 emission, CH_4 uptake, and N_2O emission will increase by 11 %, 22 % and 13 % in 50 years, respectively. The temperature increase in southeast Asia by 2100 is predicted to be approximately 3.3 °C for an A1B climate change scenario, but the prediction ranges from 2.3 to 4.9 among global models[7]. The magnitude of future increases in temperature is still uncertain, but continuous increasing trends are certainly predicted. To date, obvious increasing/decreasing trends in precipitation have not been observed in Japan, but an approximately 9 % increase in precipitation, ranging from 2 % to 20 %, is predicted in southeast Asia under the A1B scenario[7]. Future increasing trends in precipitation will have a significant effect on soil GHG fluxes, especially for CH_4 and N_2O. The increasing trend of atmospheric CH_4 concentration has been slowing over the past 20 years; therefore, the increasing trend of CH_4 uptake may be slower in the future than is predicted here.

Our study reveals that the total soil CO_2 flux in Japan's forests is equivalent to approximately 39 % of the total emissions from fossil-fuel combustion and other anthropogenic activities in Japan (350 Tg C yr^{-1}, in 2008) [12]. Under the Kyoto Protocol, countries are allowed to count forest carbon sinks, both plant and soil sinks, to meet emission reduction targets during the commitment period (2008−2012). One of the most important implications suggested for the Kyoto accounting in this study is the impact that the inter-annual variations of soil CO_2 flux will have on the accounting. Our study shows that at the national scale, soil CO_2 flux has large inter-annual variations. For example, the difference between the maximum flux (observed in 2004) and the minimum flux (observed in 1993) is approximately 15 Tg C yr^{-1}, which is greater than Japan's national forest sink target (13 Tg C yr^{-1}). Although plant carbon fixation should be taken into account, interannual variations of soil CO_2 flux would substantially affect national scale forest carbon sinks during the 5-year commitment period of the Kyoto Protocol. Another implication is that the increasing trend of the soil CO_2 flux may be diminishing forest carbon sinks: our study suggested that soil CO_2 flux has been increasing at a rate of 0.31 Tg C yr^{-2} (0.23 % yr^{-1}). Unless forest plant sinks increased more during the past three decades than the soil CO_2 flux[13], the carbon sinks in Japan's forest should be decreasing. Climate trends vary globally among regions and countries; therefore, the resulting changes in soil CO_2 flux could favour some countries' mitigation efforts but work against others.

A relatively simple model framework was used to estimate the national-scale soil GHG fluxes and their climate-driven changes. Our modelling framework did not include detailed processes, which is a limitation in our approach. For example, changes in soil quality and quantity and interactions between plant and soil may need to be incorporated, especially for predictions of long-term changes. Still, approaches using simple models such as ours have certain advantages and are important[10, 14, 15]. First, simple models have a smaller number of parameters than process-oriented models, and the parameters in simple models can be statistically determined based on multisite observation data (data-oriented) [10]. Our GHG submodels were data-assimilated using data observed at 36 sites in Japanese forests through Bayesian calibration[16] and therefore provide more data-oriented estimates than do process-oriented models. Second, simple models provide benchmarks against results from more detailed, process-oriented models[14, 15]. Our study gives estimates of soil GHG changes driven only by climate. It will be insightful to compare our estimates with those from more detailed models that include not only climate change but also changes in soil and plant-soil interactions. Another potential limitation is that soil gas flux submodels parameterised with data observed over 3 years were extrapolated to estimate fluxes over the past 30 years. Similar to the limitation raised above, possible changes in soil and plant-soil interactions may affect parameters in soil gas flux submodels. Comparing our results with those from more detailed models would help to clarify the effect of this limitation. Long-term monitoring data are also important for parameterisation and validation. Finally, long-term, regional assessments using models generally suffer from the mismatches of both temporal and spatial scales between observations and modelling. The mismatches often hinder parameterisations and validations of models, but model-data synthesis, like the Bayesian approach adopted in this study, is expected to bridge these mismatches[17].

Methods

Model overview. We combined submodels of soil temperature, water, and GHG fluxes (Supplemental Information, Fig. S1) and calculated soil GHG fluxes at a 1-km resolution. A monthly time step was adopted, and the inputs for the model were monthly mean air temperature and monthly precipitation. Soil physical and chemical properties were also required. The soil temperature submodel calculates the soil temperature using the mean air temperature and snow cover, and the soil water submodel calculates water-filled pore space (WFPS) using air temperature, potential evapotranspiration[18], and precipitation. Soil water characteristics are estimated by a generalised soil-water relationship[19]. We used the simple soil greenhouse gas models for soil GHG fluxes (SG models) [16]. The models require three inputs: soil physiochemical properties, WFPS, and soil temperature. The SG models were calibrated using the Bayesian calibration scheme against data from 36 sites in Japanese forests. We used flux data observed between 2002 and 2004. CH_4 emission was not included in this modelling because it is not dominant in most Japanese forest soils. For the CH_4 submodel, we included the effect of the atmospheric CH_4 concentration. The trends in the fluxes were examined by linear regression analysis. The analysis was performed using the R statistical computing software (version 2.11.1) [20].

Driving data. We used datasets for climate, vegetation and soil with a 1-km resolution. The climate inputs used in our model were monthly precipitation (mm) and air temperature (°C) from 1979 to 2009. We used the Meshed AMeDAS dataset[21], which is calculated by the interpolation of AMeDAS meteorological data (Automated Meteorological Data Acquisition System, the Japan Meteorological Agency). The land-cover dataset from the Japan Integrated Biodiversity Information System (J-IBIS) was used in this study. The raster soil map of the Digital National Land Information was also used in this study. The soil physical and chemical properties were derived from the Soil Data Browsing system[22].

See Supplementary Information for more details.

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Acknowledgements

This research was financially supported by FFPRI, Japan, and partly by the Development of mitigation and adaptation techniques to global warming in the sectors of agriculture, forestry, and fisheries. We thank Dr. Kazuhito Morisada for the Soil Data Browsing system database.

Author contributions

S.H. performed the modelling; M.T., S.T. and S.I. conducted the observations; S.H. wrote the manuscript; and M.T. and S.I. provided input to the manuscript.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

Competing Financial Interests: The authors declare no competing financial interests.

How to cite this article: Hashimoto, S., Morishita, T., Sakata, T. & Ishizuka, S. Increasing trends of soil greenhouse gas fluxes in Japanese forests from 1980 to 2009. *Sci. Rep.* **1**, 116; DOI:10.1038/srep00116 (2011).