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Contents

An Automated-Chamber Network for Evaluation of Carbon Budget of Asian Terrestrial Ecosystems

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1. Introduction

The world's soils contain about 1,550 Pg of organic carbon, which is more than twice the amount in the atmosphere (IPCC, 2007). On the other hand, the soil respiration, the second-largest terrestrial carbon flux after gross primary production (GPP), from global terrestrial ecosystems was estimated to be 98 ± 12 Gt C in 2008, of which 13%, 20% and 67% are contributed respectively by boreal, temperate and tropical ecosystems. Moreover, between 1989 and 2008, the global soil respiration increased by 0.1 Gt C yr^{-1}, which is about 10% of global terrestrial carbon sink (Bond-Lamberty and Thomson, 2010; IPCC, 2007). Furthermore, by using a process model (CASA), the annual global heterotrophic respiration was estimated to contribute about 71% of total soil CO_2 efflux (Potter and Klooster, 1998). Therefore, relatively small change in the carbon flow into or out of soils can potentially strongly influence the global cycles of carbon, nitrogen, and water. To date, most of the carbon-climate models employ exponential functions to predict heterotrophic respiration with a Q_{10} of about 2.0. In these models, global heterotrophic respiration increases exponentially with climate warms at an average rate of 6.2% per degree, and resulting in that the current carbon sink of terrestrial ecosystems probably shift to a carbon source after 2050. It has been reported that positive feedback from enhancement of heterotrophic respiration by global warming would raise the CO_2 concentration in the atmosphere by 20-224 ppm by 2100, and that these higher CO_2 levels would lead to an additional temperature increase ranging between 0.1 and 1.5 °C (Friedlingstein et al., 2006; IPCC, 2007). However, modeling prediction is very difficult to validate using measurements because soil respiration is highly spatially and temporally variable.

2. A multichannel automated chamber system

Soil respiration is usually measured with chamber-based techniques. Liang et al. (2003) designed a multichannel automated chamber system (multichannel LAC) that applied a steady-state technique to measure soil respiration throughout four seasons. However, the pressure inside the chamber is 0.22 Pa higher than that outside the chamber, which is likely to lead to underestimation of the actual R_s (Fang and Moncrieff, 1998). Therefore, we modified and improved this system using a flow-through, non-steady-state design (Liang et al., 2010). In brief, the multichannel LAC consists of a control unit that is a field access case, and 12 to 24 automated chambers. The main components of the control unit include a micro infrared gas analyzer (IRGA), a data-logger, two valve manifold (LAC-FL451959, CKD Corp., Komaki, Aichi, Japan). Based on the number of chambers to be equipped, the control unit can be assembled with either a small water-proofed plastic case (53 m long ×43 m wide ×21 cm high; 1550, Pelican Products, Inc., Torrance, CA, USA) for maximum 12 chambers (LAC-12G, National Institute for Environmental Studies (NIES), Tsukuba, Japan), or an aluminum case (60 m long × 40 m wide × 40 m high; SS8800; Daito Co.Ltd., Tokyo, Japan) for maximum 24 chambers (LAC-SW024, NIES) (Fig. 1). Based on the study objective and funding availability, the control unit of LAC can adopt the IRGA such as LI-840 or LI-820 (LI-COR, Lincoln, NE, USA), PGA (ADC BioScientific Ltd., Hoddesdon, England), or a modified (pressure and temperature compensation) micro CO_2 module (K30FR, SenseAir AB, Delsbo, Sweden) (Fig. 2). The standard automated chambers (90 cm long ×90 cm wide × 50 cm tall) are constructed of clear acrylic plastic sheets (1-2 mm thick) glued to an aluminum frame (Fig. 3). Between measurements, the two sections of the chamber lid are raised to allow precipitation and leaf litter to reach the enclosed soil surface, thus keeping the soil conditions as natural as possible. The chamber lids are raised and closed by two pneumatic cylinders (LAC-G90, CKD Corp.,

Fig.1. Control units of the multichannel automated chamber system. a: the unit for equipping maximum twelve chambers; b: the unit for equipping maximum twenty four chambers.

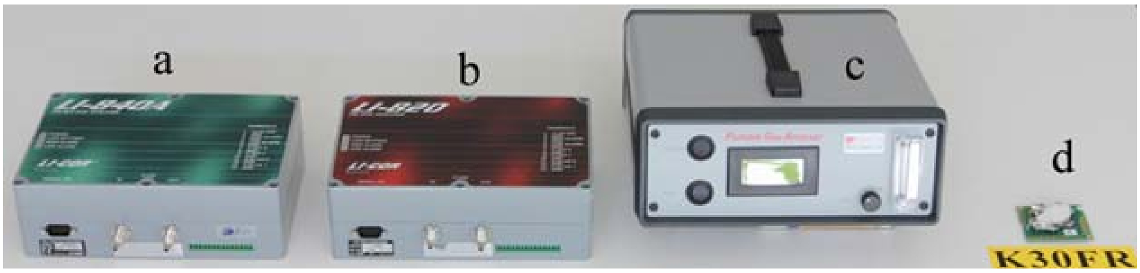

Fig.2. Non-dispersive infrared CO_2 analyzers can be used by LAC. a: LI-840 (Li-Cor); b: LI-820 (Li-Cor); c: PGA (ADC); d: K30FR (SenseAir).

Fig.3. The standard automated chamber of LAC.

Fig.4. Image of solar power for LAC.

Hitachi Industrial Equipment Systems Co.,Ltd., Tokyo, Japan). During the measurement, the chamber is closed and the chamber air is mixed by two micro fans (MF12B, Kyoei Tsushin Ltd., Tokyo, Japan). The chamber air is circulated through the IRGA by a 5 L min-1 diaphragm pump (CM-50, Enomoto Micropump Ltd., Tokyo, Japan), and the change in the CO_2 concentration is measured by the IRGA. Open and close of the chambers are controlled by a home-made relay board that is programmed by the datalogger (CR1000, Campbell Scientific Inc., Logan, UT, USA). The average power consumption of the whole system is about 13 W; thus the system can be continuously driven by three 125-W solar cells coupled with three 120-A·h deep-cycle batteries (Fig. 4).

Fig.5. A portable LAC used in a Malaysian tropical forest (left) and a portable LAC equipped with two transparent automated chambers (right) used in a Malaysian rubber plantation.

3. A portable automated chamber system

Based on the above multichannel LAC, we have been developing a portable automated chamber system (portable LAC), mainly for characterizing the spatial variation of soil respiration (Liang, 2006; Yao et al., 2012). In brief, the portable LAC has a flow-through, non-steady-state design, and comprises a portable control unit and 2 portable automated chambers (Fig. 5). The control unit is assembled with a water-proofed plastic case (53 m long ×43 m wide ×21 cm high; 1550, Pelican Products, Inc.) that comprises with a micro IRGA, a data-logger, and a home-made relay board. For measuring soil respiration, the cylinder-designed chambers (30 cm in diameter by 30 cm in height) are constructed by 3 mm thick aluminum. However, for measuring net ecosystem productivity (NEP) of ecosystems with short vegetation (such as grassland), the transparent chambers with medium size (50 cm long ×50 cm wide × 50 cm tall) are equipped (Fig. 5b). The portable LAC can continuously work for minimum 15 hours with an internal Li-ion battery (GT5, G-Tech Ltd., Tokyo, Japan). The chamber lid is raised and closed by a pneumatic cylinder (LAC-G50, CKD Corp.) at a pressure of about 0.2 MPa from a 5 L aluminum tank that is assembled inside the control unit. The high pressure air is generated by a micro air compressor (LAC-Com10, Maxway Electric Industrial Ltd., Taoyuan, Taiwan) that can be powered either by the internal Li-ion battery or by the cigarette power of car (Fig. 6). In addition, soil temperature and soil moisture are monitored using an E-type thermocouple probe (MHP, Omega Engineering, Stamford, USA) and TDR sensor (SM150, Delta-T Devices Ltd.), respectively.

4. Partitioning of CO_2 budget at forest floor

The multichannel LAC is initially applied for continuous measurement of soil respiration at different forest ecosystems. For example, in the autumn of 2002, we installed a LAC with 24 chambers at the Tomakomai Flux Research Site at a 45-year-old Japanese larch (*Larix kaempferi* Sarg.) plantation. The 24 chambers distributed randomly on the forest floor within a circular area 40 m in diameter (Fig. 7). The 24 chambers were divided into three groups, each with 8 chambers. The first group of chambers was used to measure total soil CO_2 efflux (R_s), in which the understory vegetation was clipped periodically during the growing season. The second group was used to measure heterotrophic respiration (R_h) by installing the chambers in 1 × 1 m root exclusion plots. The third group (chamber size: 90 cm long ×90 cm wide × 100 cm tall) covered the understory vegetation, thus it could directly measure carbon sequestration of the forest floor.

Fig.6. A micro powerful DC air compressor powered by a vehicle cigarette for filling the air tank inside the portable LAC.

Fig.7. Chamber distribution at forest floor of a larch plantation.

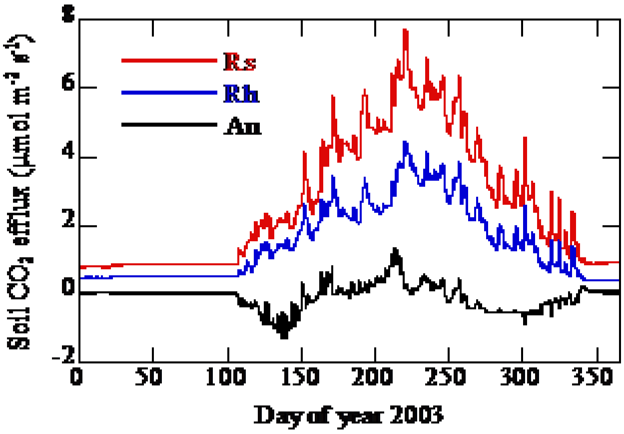

Fig.8. Seasonal changes in total soil respiration (R_s), heterotrophic respiration (R_h) and undergrowth CO_2 sequestration at Tomakomai larch forest.

Over the course of an hour, the 24 chambers were closed sequentially and the sampling period for each chamber was 150 s. Therefore, the chambers were open for 96% of the time. During each 1-h cycle, each chamber was open for 57.5 minutes and closed for 2.5 minutes. Thus, most of rainfall and leaf litter could enter the chambers, and the interior of each chamber had good exposure to any atmospheric turbulence. Air temperature at about 25 cm height inside each chamber was measured with a home-made T-type thermocouple. Soil temperature profile at 5, 10, 20, 30 and 50 cm depths were measured with the home-made E-type thermocouples. In addition, volumetric soil moisture at 10 cm depth was monitored in nine selected chambers (three for each group) with TDR sensors of CS616 (Campbell Scientific). All of the sensors were recorded using a CR1000 data-logger via a home-made 62 differential-channel multiplexers. The data-logger acquired outputs from the IRGA and other sensors at 1-s intervals and recorded the averaged values every 10 s. Soil respiration (R_s, μmol m^{-2} s^{-1}) was calculated using the following equation:

$$R_s = \frac{PV}{RS(T+273)}\left(\frac{\partial C}{\partial t} + \frac{C}{(1000-W)}\frac{\partial W}{\partial t}\right) \qquad (1)$$

where V is the effective chamber-head volume (cm^3), S is the measured soil surface area (cm^2), P is the air pressure (hPa), R is the gas constant (8.314 Pa m^3 K^{-1} mol^{-1}), T and W are the air temperature (°C) and water vapor mole fraction (mmol H_2O mol^{-1}) inside the chambers, respectively, $\partial C/\partial t$ and $\partial W/\partial t$ are the rate of change in the CO_2 mole fraction (μmol CO_2 mol^{-1} s^{-1}) and water vapor mole fraction (mmol H_2O mol^{-1} s^{-1}), respectively.

Note that the pressure is the pressure inside the chamber but not the pressure inside the IRGA, because the pressure inside the IRGA is generally several kPa higher or lower than that of atmosphere depending on the installation position of the air sampling pump. However, the W section can be ignored due to it only contributes less than 1% to R_s as well as most of the commercially available IRGA cannot be able to measure water vapor. Therefore, air pressure at 30 cm height around the center of the measurement plots was monitored with a high precision pressure transducer (PX2760, Omega Engineering, Inc., Stamford, CT, USA).Fig. 8 shows the forest floor CO_2 budget for Tomakomai larch forest in 2003. Annual R_s and R_h were measured to be 9.6 and 5.5 t C ha^{-1} yr^{-1}, respectively. Moreover, annual CO_2 sequestration by the understory vegetation was estimated to be about 0.4 t C ha^{-1} yr^{-1} (Liang et al., 2004).

Fig.9. Chamber distribution at the Teshio CC-Lag flux site.

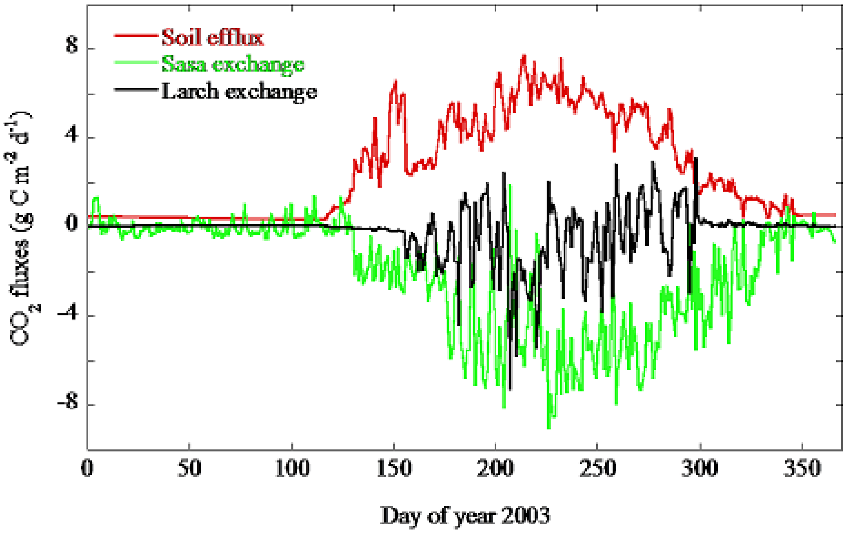

Fig.10. Seasonal changes in soil respiration (efflux) and CO$_2$ sequestration by dwarf bamboo (Sasa exchange) and larch trees (Larch exchange) at the Teshio CC-Lag flux site.

5. Partitioning of NEP of grassland and wetland

Because of the transparency of the automated chambers, they can be also applied for directly measuring NEP for ecosystems with low vegetation. For example, in the spring of 2004, we installed a LAC with 24 chambers at the Teshio flux site, in the Teshio Experimental Forest of Hokkaido University (45°03'N, 142°06'E, 66 m elevation), northern Hokkaido, Japan. This site is a primary conifer-broadleaf mixed forest with 15% of the trees logged in 1961. A clear-cut harvesting event was conducted during the snow-cover season between January and March 2003. However, the site was planted with hybrid larch (*L. gmelinii* × *L. kaempferi*) seedlings with the density of 2500 stem ha^{-1} in late October, 2003. The 24 chambers were divided into three groups, each with 8 chambers. The first group of chambers was used to measure the total soil respiration (R_s), in which the vegetation was clipped periodically during the growing season. The second group (chamber size: 90 cm long ×90 cm wide × 150 cm tall) covered the dense undergrowth of evergreen dwarf bamboo (*Sasa senanensis*). The third group (chamber size: 90 cm long ×90 cm wide × 200 cm tall) covered the young larch trees (Fig. 9). Thus the multichannel LAC could partition the NEP into soil respiration, carbon sequestrations by larch trees and dwarf bamboo, respectively (Fig. 10) (Takagi et al., 2009). Following the Tomakomai flux site was destroyed by a strong typhoon in September 2004, we installed a multichannel LAC with 18 chambers in 2005 for monitoring the carbon budget with vegetation natural regeneration. We applied 5 chambers for measuring total soil respiration, 5 chambers for measuring heterotrophic respiration, 5 chambers for measuring NEP by covering vegetation, and 3 chambers for measuring decomposition of the stumps (Fig. 11) (Sano et al., 2010). Recently, we have installed multichannel LAC at a wetland on the Tibetan Plateau (Yu et al., 2013) and an arid grassland in Inner-Mongolia for continuous measurements of NEP and heterotrophic respiration (Fig. 12).

Fig.11. Chamber distribution at Tomakomai flux site after typhoon.

Fig.12. A multichannel LAC installed at a Inner-Mongolian arid grassland.

6. Measurement of spatial and temporal variations of soil respiration

Even the above multichannel LAC is generally installed at flux sites for direct inter-comparison with tower-based eddy covariance (EC) measurements and/or calibrating the nighttime ecosystem respiration obtained by EC method, the portable LAC is an effective protocol for comparing the spatial and temporal variations of soil respiration among different ecosystems. Since 2010, we have been using the portable LAC to evaluate the effects of land-use and land-use change on soil degradation of a tropical rainforest in the Pasoh Forest Reserve (2º58’N, 102º18’E), Peninsular Malaysia. We installed 30 soil collars at each ecosystem. The collars were placed on a 5x5 m mesh. The portable LAC was operated on a continuously sequential measurement mode. We set the sampling period for each point as 3 min. Therefore, the measurement over the 30 points took one and half hours (Fig. 13).

Soil respiration among the 30 measurement points was 6.65 ± 1.98, 6.60 ± 2.39, 3.99 ± 1.49, and 3.17 ± 0.94 μmol CO_2 m^{-2} s^{-1} for a primary forest, a logging site that was selectively logged five years ago, a 50-year-old secondary forest, and a 4-year-old rubber plantation, respectively. Result suggests that logging event could enhance soil respiration by increasing the decomposable substitutes, although it had reduced 50-65% of root respiration. Moreover, land-use change would significantly reduce soil respiration through inducing soil degradation.

Fig.13. Measuring spatial variations of soil respiration using portable LAC at a secondary forest (a) and primary forest (b) in Pasoh of Peninsular Malaysia.

7. Potential monitoring no CO_2 GHGs budget

Currently, both multichannel LAC and portable LAC are used only for measuring CO_2/H_2O. The capacity of the sampling air pump is 5 L min^{-1}. It can also provide enough sampling air for an additional analyzer for measuring other no CO_2 GHGs. For example, in 2010, we installed a multichannel LAC with 20 chambers at the Luanhaizi wetland, northeastern the Tibetan Plateau (37°35'N, 101°20'E, 3,200 m a.s.l.). This multichannel LAC was equipped with both a CO_2/H_2O analyzer (LI-840, Li-Cor) and a CO_2/CH_4/H_2O analyzer (G1301; Picarro Inc., Santa Clara, CA, USA). It could simultaneously monitor CO_2/CH_4/H_2O fluxes of the ecosystem (Fig. 14). Moreover, result could be also used for cross-check of NEP that obtained by the two different analyzers (Yu et al., 2013). In 2011, we installed a multichannel LAC with 12 chambers at an arid grassland site in Inner-Mongolia (44°08'N, 116° 19'E, 1030 m). This multichannel LAC was equipped with both a CO_2/H_2O analyzer (LI-840, Li-Cor) and an isotopic CO_2 analyzer (G1101; Picarro Inc.) (Fig. 15). Therefore, in addition to NEP, this chamber system could also monitor isotopic CO_2 flux of the grassland ecosystem.

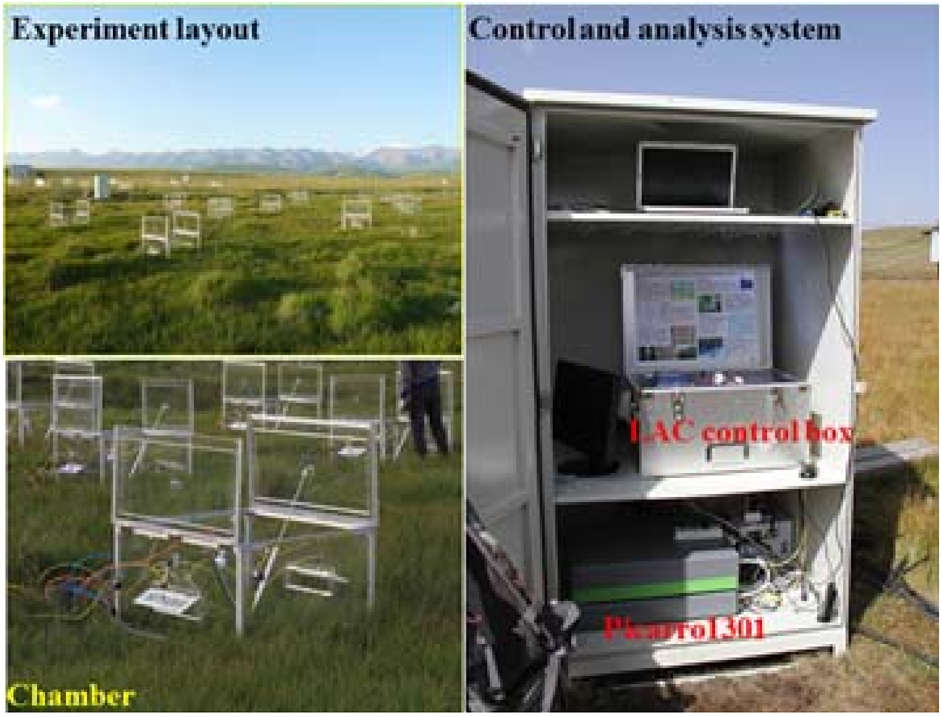

Fig.14. A multichannel LAC coupled with both CO_2 and CH_4 analyzers for measuring CO_2 and CH_4 fluxes at a wetland on Tibet Plateau.

Fig.15. A multichannel LAC coupled with both CO_2 and isotopic CO_2 analyzers for measuring NEP and isotopic CO_2 flux at a Mongolian arid grassland site.

Fig.16. A multichannel LAC applied in a soil warming experiment.

8. Soil warming experiment

Since 2006, we set up seven soil warming experiments at seven typical forest ecosystems, including a 35-year-old cool-temperate mixed forest in northern Hokkaido (Teshio of Hokkaido University Forest), a 70-year-old deciduous oak forest in northeastern Japan (Shirakami maintain range), a natural beech forest (>100-year-old) in Hokuriku region (Mt. Naeba), a 55-year-old Japanese red pine forest in Kantou region (Tsukuba), a 30-year-old ever-green Japanese oak forest in Setonaikai region (Higashi-Hiroshima), a 55-year-old subtropical evergreen forest in Kyusyu (Miyazaki University Forest) of Japan, and a subtropical evergreen forest in Mt. Ailao in Yunnan province, southwestern China (Liang, 2009). We installed multichannel LAC with 15 to 20 chambers (90 cm long ´ 90 cm wide ´ 50 cm tall) at each site with 5 chambers for measuring total soil respiration, 10 chambers for measuring heterotrophic respiration that placed at 100 x 100 cm root exclusion plots (40 cm in depth). The other 5 chambers were used for optional measurements, such as litter decomposition or soil moisture treatment. Half of the trenched plots at each site were used for soil warming experiment, and another half of the trenched plots were used as control plots by keeping them in the ambient environment. For the soil warming plots, an 800 W infrared heater was vertically hanged over the center of the plot at about 170 cm above the soil surface (Fig. 16). Compared to the control plots, the infrared heater could warm the soil for 3.0, 2.5, 2.0, 1.7, and 1.5°C at depths of 0, 5, 10, 20, and 30 cm, respectively (Aguilos et al., 2011).

9. Automated chamber network

Terrestrial ecosystems in Asia cover large land area and represent various biomes including tundra, boreal, temperate and tropical forests, wetlands, grasslands, crop fields, and the world largest rice paddies extending from the arctic circle to equator. Therefore, knowledge of the carbon budget of the terrestrial ecosystems in Asian region is essential to advance our understanding about the global carbon cycle and prediction of the impacts of climate change. Since the mid-1990s, we have been installing the multichannel LAC in a tundra in the West Siberian lowland (56°51'N, 82°50'E), a boreal forest in central Alaska (64°52'N, 147° 51'W), cool-temperate and temperate forests in Japan, Korea and China, subtropical forests in Japan, Mainland China (Tan et al., 2013b) and Taiwan, tropical seasonal forests in China and Thailand, tropical rainforests in China and Malaysia (Tan et al., 2013a), and even arid grasslands in Inner-Mongolia and wetlands on the Tibetan Plateau, for continuous measurements of forest floor CO_2 budget as well as NEP (Fig. 18). Among the sites, 7 systems are used for conducting soil warming experiments. Currently, the chamber network is expanding rapidly in the Asian region. Our ultimate objective is to estimate the carbon budget of Asian terrestrial ecosystems as well as its response and feedback to regional climate change.

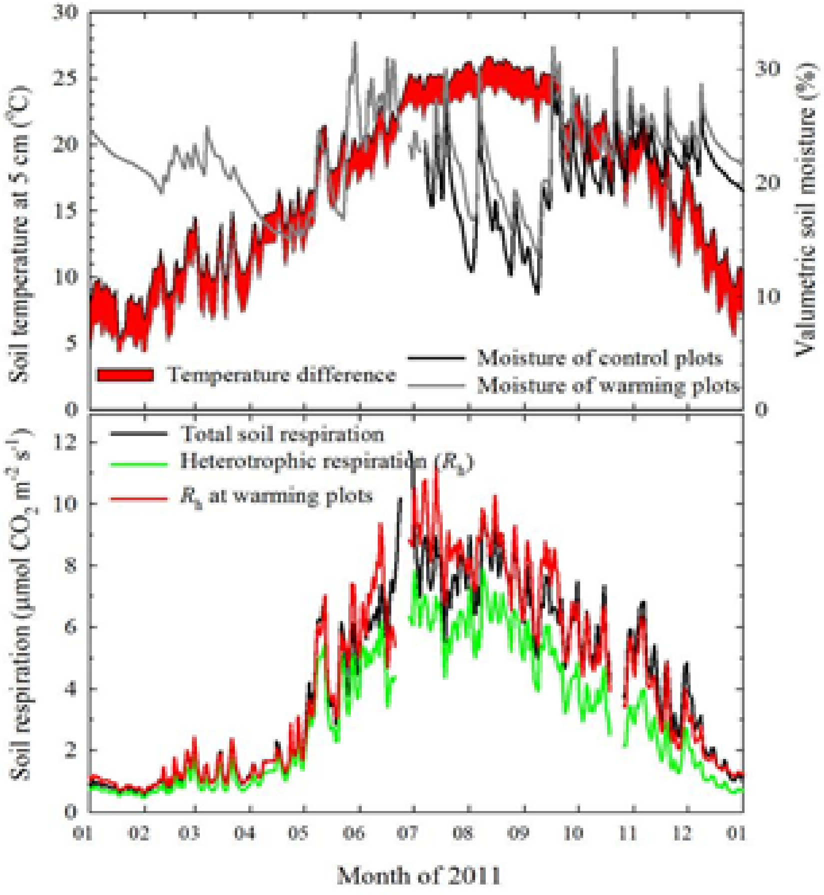

Fig.17. Seasonal changes in soil temperature, volumetric soil moisture and soil respiration at a subtropical forest in Miyazaki, Kyusyu of Japan.

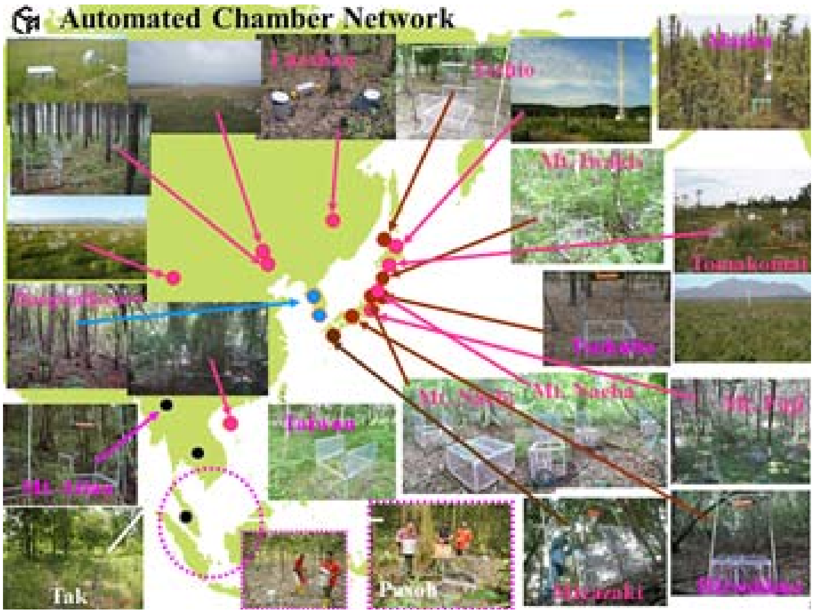

Fig.18. An automated chamber network for evaluating carbon budget of Asian terrestrial ecosystems.

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