Landscape level carbon and water balances and agricultural production in mountainous terrain of the Haean Basin, South Korea

Lee, B. (1); Tenhunen, J. (1); Geyer, R. (1); Seo, B. (1); Li, Y. (2); Kang, S. (3)

(1) Department of Plant Ecology, University of Bayreuth, 95440 Bayreuth, Germany, puplebr@gmail.com

(2) South China Botanical Garden, CAS, Guangzhou 510650, PR China

(3) Department of Environmental Science, Kangwon National University, Chuncheon, South Korea

Abstract: The process-based spatial simulation model PIXGRO is being developed to estimate gross primary production, ecosystem respiration, net ecosystem CO_2 exchange and water use by forest and crop fields of Haean Basin, South Korea at landscape scale. Simulations are run for individual years from early spring to late fall, providing estimates for dryland crops and rice paddies with respect to carbon gain, biomass and leaf area development, allocation of photoproducts to the belowground ecosystem compartment, and harvest yields. In the case of deciduous oak forests, gas exchange is estimated, but spatial simulation of growth over the single annual cycles is not included. Spatial parameterization of the model is derived for forest LAI based on remote sensing, for forest and cropland fluxes via eddy covariance and chamber studies, for soil characteristics by generalization from spatial surveys, for climate drivers by generalizing observations at ca. 20 monitoring stations distributed throughout the basin and along the elevation gradient from 500 to 1000 m, and for incident radiation via modelling of radiation components in complex terrain. Validation of the model is being carried out at point scale based on comparison of model output at selected locations with observations of LAI, biomass, fluxes and crop yield, as well as with known trends in ecosystem response documented in the literature and regional statistical data. The resulting modelling tool is useful for estimation of ecosystem services at landscape scale, first expressed as kg ha^{-1} crop yield, but via future cooperative studies also in terms of monetary gain to individual farms and farming cooperatives applying particular management strategies.

Key words: Landscape gas exchange; mountain ecology; crop yield; up-scaling; ecosystem services

Introduction

The influence of land use on carbon and water balances of mountainous terrain and the yield of crops as ecosystem services is determined by the complex behaviour of different ecosystem types along topographic and climate gradients and their response to management practices. To assess such landscape response, a process-based spatial simulation model (PIXGRO) is being developed that provides estimates of gross primary production (GPP), ecosystem respiration (Reco), net ecosystem CO_2 exchange (NEE), water use by the vegetation, and growth and yield of crops in Haean Basin, South Korea. The model takes into account the strong influences of relief on radiation input (Wang et al. 2005, 2006), temperature and humidity, and the shifts in ecosystem processes along elevation gradients that have been documented (Tenhunen et al. 2009).

PIXGRO is designed as a tool for bridging between measured gas exchange fluxes, derived parameters for carboxylation capacity, seasonal changes in biomass and structure in the case of herbaceous and crop plants, and biomass yields, taking into account specific ecophysiological behaviour of individual species. While the application of eddy covariance methodology during the last decade has provided new insight on gas exchange of most ecosystem types (Baldocchi et al. 2001, 2003), the linkage of observed carbon fixation fluxes to plant development, and feedbacks between development and fluxes, still requires considerable investigation and quantification. PIXGRO focuses on this linkage, describing gas exchange on an hourly time step, and plant growth and phenology on a daily basis via simple classical growth and carbon allocation routines derived in agronomic studies (cf. Adiku et al. 2006). Direct comparisons between model simulated response and ecophysiological field studies are being made. Further validation is being carried out with respect to seasonal development in biomass observed in sequential harvests as well as estimated via remote sensing.

While the model is one-dimensional and is applied across landscape maps without interactions, it nevertheless can provide new insight and a new perspective, since assembling the required data bases along strong climate gradients, estimating ecosystem response in a spatial context, and integrating ecosystem performance may lead to non-intuitive influences on overall carbon and water balances (Tenhunen et al. 2009). In the current version of the model, the landscape of Haean Basin (Fig. 1A and 1C) is analyzed only with respect to three land use categories; namely, the mixed-deciduous forest vegetation belt, the dryland farming zone considered for a general root crop (planting in this zone is dominated by potato, radish, *Codonopsis* and ginseng root crops), and the rice paddy area. Our ongoing research is devoted to further developing the potential of PIXGRO to separately estimate yield and economic gains for as many as 10 crop types in the dryland farming zone, a step that is essential for use of PIXGRO as an evaluation tool in global change scenarios.

1. Materials and Methods

1.1. Site description

Haean Basin is located northeast of the city of Chuncheon in Yanggu County between longitude 128° 5' to 128° 11' E and latitude 38° 13' to 38° 20' N with a range in altitude from ca. 500 m to 1100 m (see Figs. 1B). The average annual air temperature is ca.10.5°C at valley sites and ca. 7.5°C at the northern ridge line. Average precipitation is estimated at 1200 mm with 50% falling during the summer monsoon. The forest vegetation is diverse but dominated by oak species. The major tree species include *Quercus dentata*, *Q. mongolica*, *Q. serrata*, *Betula davurica*, and *Tilia amurensis*. Major species of the understory are *Q. mongolica*, *Weigela florida*, *Stephanadra incisa*, *Ulmus laciniata*, *Symplocos chinensis*, *Euonymus alatus*, *Acer pseudosieboldianum*, and *Corylus heterophylla*. Rice paddies cover ca. 25% of the cropland area in the Haean Basin. Dryland farms include potato (15% of cropland area), radish (20%), cabbage (15%), beans (5%), *Codonopsis pilosula* and ginseng (together 5%) as well as relatively new plantings of fruit trees and miscellaneous other crops.

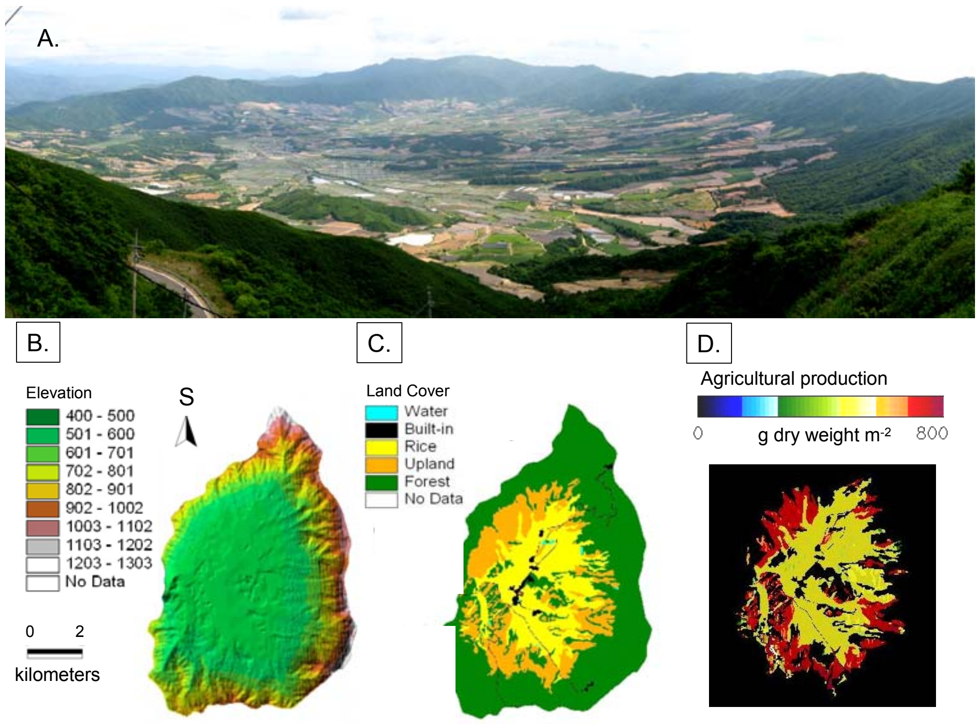

Figure 1. A. View of the Haean Catchment landscape from the north rim looking south. B.,C.,D. Corresponding digital elevation model, land cover, and an initial output prediction for agricultural production in dryland farms and rice paddies with the model PIXGRO from the same view to the south.

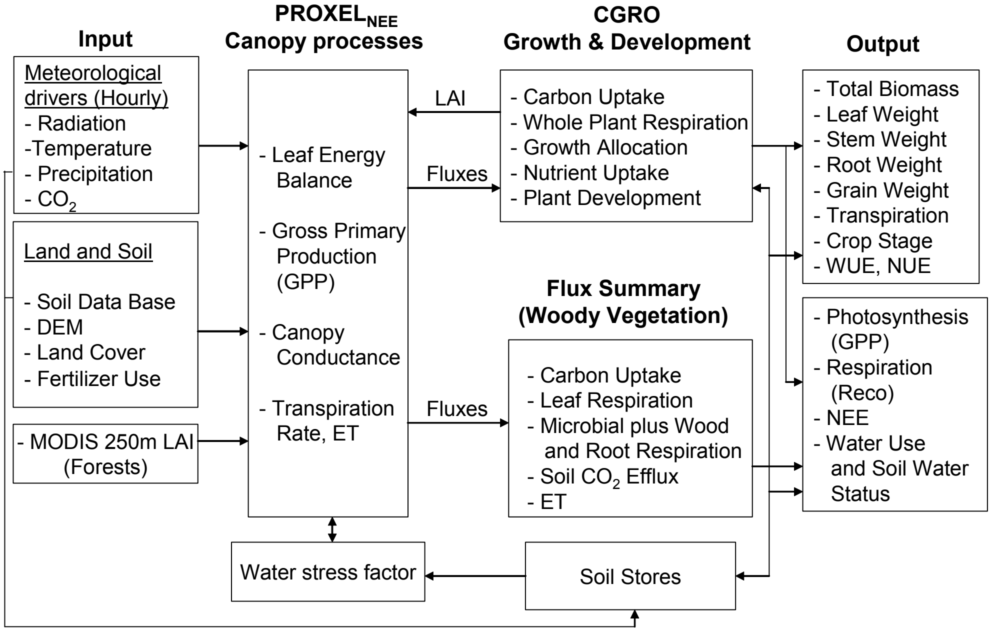

Figure 2. Diagram of the PIXGRO model, indicating the processes in the sub-models PROXEL$_{NEE}$ and CGRO. Not shown but also included in the model is a complete soil water balance and coupling of soil water status to canopy conductance. In the Haean Basin application, PIXGRO is used to estimate the CO_2 and H_2O exchange of dryland crops and rice paddies along with growth and final yield. Additionally, the PROXEL$_{NEE}$ component of PIXGRO is used together with a sub-model for ecosystem respiration (Reco) to estimate GPP, NEE and water use by deciduous forests.

1.2. Simulation model PIXGRO for CO_2 and H_2O exchange, crop growth and yield

The PIXGRO model structure may be summarized via the components illustrated in Fig. 2. Canopy conductance, canopy transpiration, evapo-transpiration, and gross primary production (GPP) are calculated with a single-layered canopy model (sub-model PROXEL$_{NEE}$) as described by Owen et al. (2007). Physiological parameters for photosynthetic processes are obtained by inversion of the canopy model with respect to gas exchange measurements obtained either from eddy covariance or ecosystem chamber studies and according to the methodologies outlined by Owen et al. (2007) and Li et al. (2007). As shown in Fig. 3, consistent seasonal trends in the key physiological parameter describing CO_2 uptake capacity, $Vc_{uptake1*}$, are found for functional crop types, e.g., root crops and rice as a grain crop (Li et al. 2010) which aids in parameterization according to the land use shown in Fig. 1C. In correlation with net photosynthesis determined via CO_2 uptake capacity, leaf stomatal conductance is calculated according to the model of Ball et al.

(1987). This step includes the behavior of stomatal conductance sensitivities to all factors influencing photosynthesis, and maintains propor-tionality in exchange of CO_2 and H_2O that is well documented.

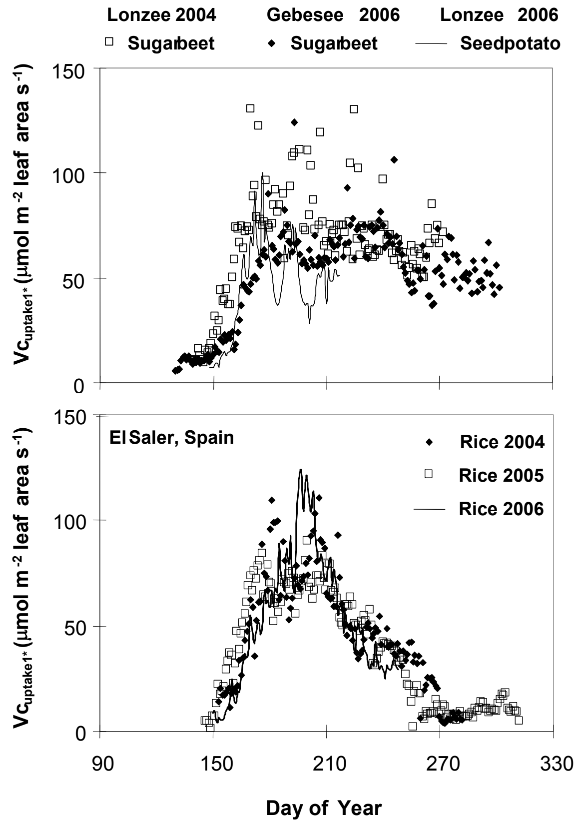

Figure 3. Seasonal course in CO_2 uptake capacity ($Vc_{uptake1*}$) for root crops and for rice with data from the sites indicated (see also Li et al. 2010). $Vc_{uptake1*}$ is a key parameter of $PROXEL_{NEE}$ (see Owen et al. 2007), determining carbon fixation and water use.

Sites with detailed information on ecosystem gas exchange (NEE, Reco, GPP, ET) and aboveground carbon pools were used to aid in model formulation and parameterization. The sites include Gwangneung near Seoul for deciduous forest (http://asiaflux.yonsei.kr/network/051GDK_1.html), Lonzee and Gebesee agricultural sites in Europe for root crops (http://www.bgc-jena.mpg.de/bgc-processes/ceip/ about/sites_eco.htm), and El Saler, Spain (same web site as root crops) and Mase paddy field site in Japan for rice (http://asiaflux.yonsei.kr/network/ 007MSE_1.html). Observations on the seasonal development of biomass and LAI at the same sites are used to estimate appropriate parameters for the allocation and growth routines of CGRO.

The current version model makes estimates of vegetation response only for single seasons with a known distribution of ecosystem types (Fig 1C; data from Korean Ministry of Environment). In this context, forested areas have a static structure (spatial patterns in maximum LAI determined via MODIS NDVI at 250 m), but croplands change in aboveground structure during the season as described by classical growth algorithms in the sub-model CGRO (cf. Adiku et al. 2006). Carbon uptake via $PROXEL_{NEE}$ along with partitioning and whole plant respiration estimates in CGRO determines the seasonal development of vegetative biomass, leaf area index (LAI), and ultimately biomass of agricultural products, i.e., agricultural yield.

Also included in the model is a soil water balance, coupling of soil water status to canopy conductance, and routines to estimate canopy water use (Reichstein 2001) as well as nutrient uptake. PIXGRO is strongly influenced by an ecophysiological perspective. Thus, signals generated by the root system as the soil layers dry, lead to patchy stomatal closure, limiting both ecosystem photosynthesis and transpiration simultaneously and in equal proportion (see review and discussion by Reichstein 2001; Reichstein et al. 2002, 2003). Additional information on the structure and procedures within PIXGRO are provided by Tenhunen et al. (2009).

1.3. Spatial framework of the simulations

Inputs to the model are hourly global radiation, air temperature, relative humidity and precipitation. Matrices for all meteorological drivers are prepared previous to simulation runs (estimated in separate routines and stored outside of the model) and are input to the model according to the hourly simulation time step. Meteorological driver data (examples in Fig. 4) are derived by smoothing information from a network of 11 Delta-T GSP1 weather stations which is supplemented by distributed HOBO logging sensors (ONSET, Bourne, MA; see also http://www. bayceer.uni-bayreuth.de/terreco/).

Soil properties with respect to the water store and distribution of crop types was provided by the Kangwon Province Development Research Institute.

For each time step in the simulation, PIXGRO results were obtained and stored for each 30 x 30 m pixel of the landscape map, and according to the land cover indicated in Fig. 1C.

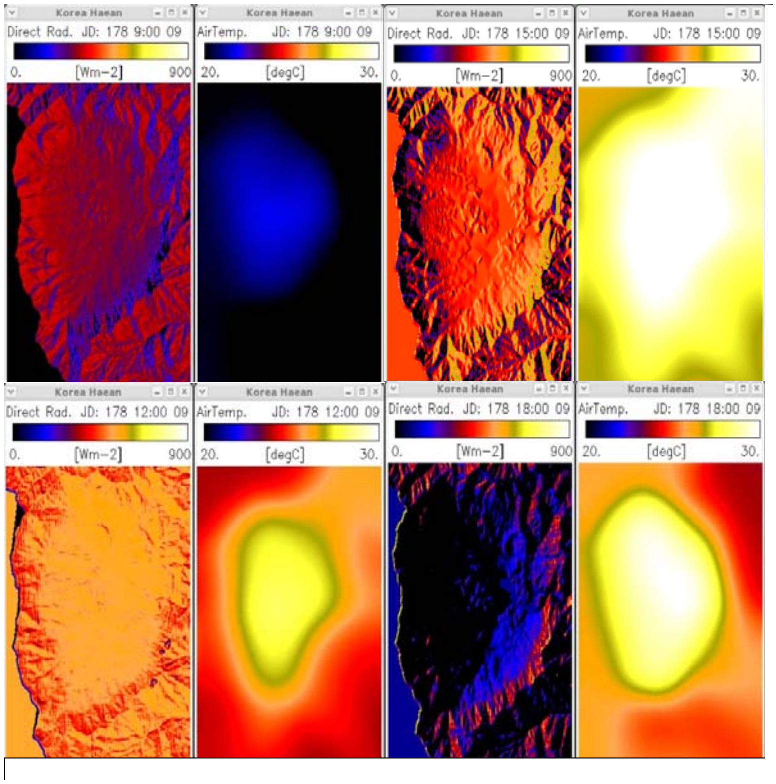

Figure 4. Patterns within Haean Basin in direct global radiation (W m^{-2}), and air temperature (°C) at 9 a.m. noon, 3 p.m., and 6 p.m. on June 27, 2009 (clear day) as examples of drivers used for the PIXGRO model simulations and derived from the meteorological station network. North is toward top of figure.

2. Illustration of Results

Two types of output are obtained in post-processing of output from the simulations: 1) hourly information on response at "Test Pixel" sites and 2) daily information on land surface processes mapped over the Haean Basin. Each can of course be integrated or modified to obtain a summary of the model simulations with different time and space scales. "Test Pixel" output is illustrated in Fig. 5. for a single 30 x 30 m rice paddy location in the center of the basin. The role of the test pixels is to provide us with the opportunity to test the model with respect to observations as they are made in ecophysiological and agricultural studies. The relationship between input and output variables may be examined on any selected day in comparison to chamber gas exchange studies, e.g., response of the vegetation canopy to fluctuations in meteorological drivers or to the soil water store. Integrating over daily periods, the seasonal change in flux components (GPP, Reco, NEE and ET) may be compared to eddy covariance estimates (Fig. 5) from different sites. The parameterization of carboxylation capacity adapted from observations in Spain (Fig. 3) along with estimated respiration components suggest a similar spring increase in GPP and NEE in Haean as at the spanish site when driven by local meteorology. However, rice in Haean has a long developmental period and is harvested only in October, while the harvest in Spain occurs early in September. By modifying parameters controlling the course of senescence, a hypothetical lengthening of the growing season occurs in the model. Ongoing flux measurements are now being used to test this hypothesis. In general, the simulated development of the crop and the coupling of CO_2 gain, allocation and yield shown in Fig. 5 is plausible and allows the desired comparisons with field observations.

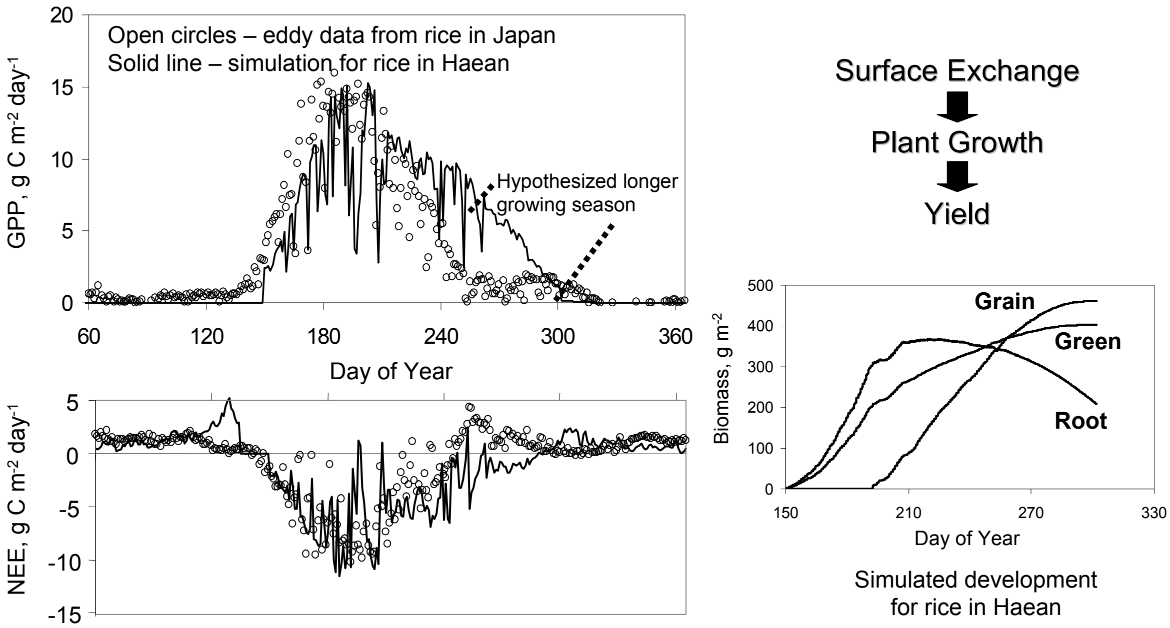

Figure 5. Simulation of daily CO_2 uptake (GPP – gross primary production) and net ecosystem CO_2 exchange (NEE) over the course of the season for a single rice paddy "test pixel" (solid line) located at the center of Haean Basin. The simulated gas exchange is compared with observations obtained via eddy covariance methodology at the Mase Asia-Flux site in Japan (open circles). Meteorological data for the simulations is not the same as observed at Mase. Allocation and senescence parameters in PIXGRO were set to extend the growing season into October (hypothesis). Also shown is the seasonal accumulation of biomass into green aboveground plant material, into roots (decreasing due to senescence in late season), and into rice grain.

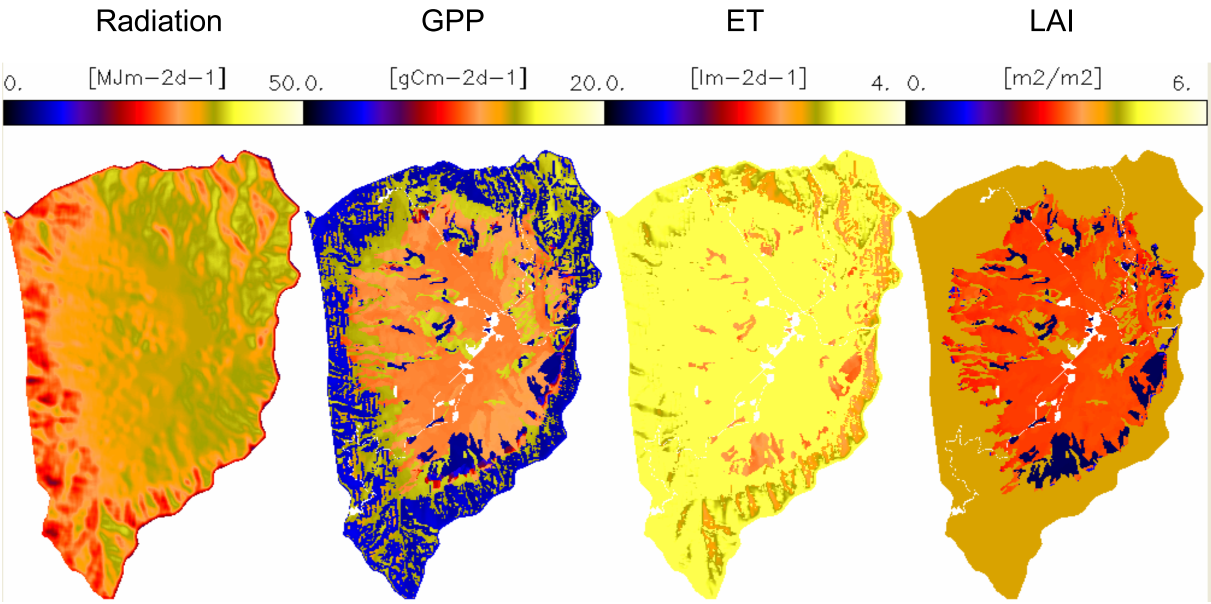

Figure 6. Daily radiation input, carbon fixation, water use and LAI of the Haean Basin on August 1, estimated with PIXGRO.

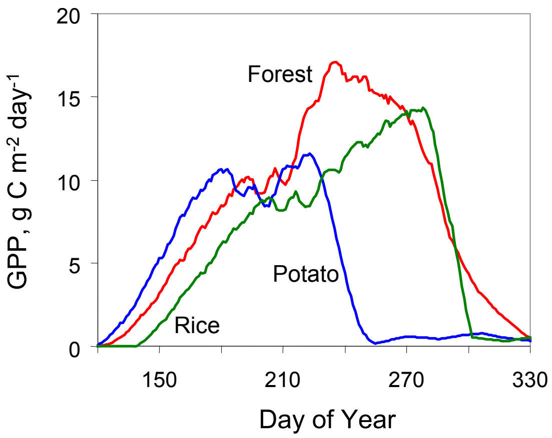

Figure 7. Simulated seasonal course of daily GPP for representative pixels of deciduous oak forest, a potato field and a rice paddy in Haean Catchment during 2009.

Crop	Planting Date DOY	Harvest Date DOY
Bean	126	289
Cabbage	141	202
Potato	121	246
Radish	146	228
Rice	137	284
Difference	**25 days**	**87 days**

Table 1. Planting and harvest dates for the most important crops grown currently in Haean Catchment. Also indicated is the length of the planting and harvest period.

The second type of output from PIXGRO is illustrated in Fig. 6, where daily radiation input, GPP, ET and LAI development in the cropland are mapped over the basin for a clear day on August 1. The map for agricultural production (Fig. 1D) similarly provides a "daily output". However, this is the accumulated biomass in rice grain and root crop tubers in each case on the day of harvest. At this stage of model development, the most important point to realize from Figs. 1D and 6 is that overall carbon and water balances as well as agricultural yield at landscape scale are determined by the spatial distribution of ecosystems having different physiological and phenological characteristics. It is essential that we gain an understanding of the influence of these factors. Differences in the seasonal course of GPP at "test pixel" sites in each of the three vegetation zones are shown in Fig. 7. While rice paddies and the natural forest in Haean influence CO_2 exchange of the landscape late into the fall, the root crop production occurs over a much shorter time period (Table 1). As in the case of GPP, there are also large differences in water use and ecosystem respiration occurring under different land use. It is quite important when discussing about landscape "performance" with respect to natural cycles that the different contributing components of the landscape mosaic be considered. In subsequent development, we intend to increase the capacity of PIXGRO in this context to estimate landscape processes and ecosystem services derived from at least 10 land use types.

3. Discussion and Conclusions

PIXGRO provides a useful landscape level tool to link land surface exchange with growth and production of the vegetation, especially with respect to the ecosystem services derived from crop production. It focuses on short-term assessments, but includes in a simple mechanistically-based fashion the multiple ways in which vegetation may respond to climate change, e.g., shifts in gas exchange capacity, in phenology and development, and in allocation of photoproducts to growth and production. The design is favourable with respect to comparisons with field observations, providing good opportunities for validation of response. The model provides advantages in landscape scale applications that focus on carbon balances with a heterogeneous vegetation mosaic, on hydrology and small catchment water balance, and on trace gas emissions from agriculture.

The model differs from many others currently in use in spatial simulations through the use of three principles. (1) Carboxylation capacity (via the Ball et al. model also water use) is determined by the key ecosystem level physiological parameter $Vc_{uptake1*}$, which can be examined for validity via both eddy covariance and chamber-based gas exchange studies. (2) Response to soil drying depends on a signal generated in correlation with water availability changes in three soil layers. In spatial simulations, both the overall soil and root system descriptions are untested. But again the coupling function relating aboveground functional changes to soil properties can be calibrated according to field studies. (3) Decreases in gas exchange due to soil drying are described according to the phenomenon of "patchy stomatal closure". The advantage is that simulated water use efficiencies of the ecosystem agree well with observations, and practically, that model photosynthesis parameters determined under non-water-stressed conditions remain valid during drought periods.

Many challenges remain, however, with respect to application of the model. We intend to extend the spatially explicit simulation of yield to include many crops. To evaluate alternatives in management in response to global change, the model must estimate services derived from at least 10 land use types, thus providing assessments that relate to decision-making by real farmers of the Haean Basin and by natural resource managers. Furthermore, sensitivities with respect to management must be included, e.g., response with respect to different types of fertilization (conventional vs. organic farming), herbivory (or application of pesticides), and weed invasions (or application of herbicides). These challenges provide a focus for our research and extension of the model.

References

Adiku S.G.K., Reichstein M., Lohila .A, Dinh N.Q., Aurela M., Laurila T., Lueers J., Tenhunen J.D., 2006. PIXGRO: A model for simulating the ecosystem CO_2 exchange and growth of spring Barley, *Ecological Modelling*, 190, p. 260–276.

Baldocchi D., Falge E., Gu L. et al., 2001. FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities, *Bulletin of the American Meteorological Society*, 82, p. 2415–2434.

Baldocchi D.D., 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, *Global Change Biology*, 9, p. 479-492.

Ball J.T., Woodrow I.E., Berry J.A., 1987. A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions, in: *Progress in Photosynthesis Research* (ed Biggins I.) p. 221-224, Vol. IV.5, Proceedings of the VII International Photosynthesis Congress.

Li Y.L., Tenhunen J., Owen K. et al., 2008. Patterns in CO_2 gas exchange capacity of grassland ecosystems in the Alps, *Agriculture and Forest Meteorology*, 148, p. 51-68.

Li Y.L., Lee B., Tenhunen J. et al., 2010. Seasonal patterns in CO_2 fixation capacity of European croplands, Submitted to *Agriculture and Forest Meteorology*.

Owen K.E., Tenhunen J., Reichstein M. et al., 2007. Comparison of seasonal changes in CO_2 exchange capacity of ecosystems distributed along a north-south European transect under non-water-stressed conditions, *Global Change Biology*, 13, p. 734-760.

Reichstein M., 2001. *Drought Effects on Carbon and Water Exchange in three Mediterranean Ecosystems*. Bayreuther Forum Oekologie, Band 89, University of Bayreuth, PhD Thesis.

Reichstein M., Tenhunen J.D., Ourcival J.M. et al., 2002. Severe drought effects on ecosystem CO2 and H2O fluxes at three Mediterranean sites: revisions of current hypothesis?, *Global Change Biology*, 8, p. 999-1017.

Reichstein M., Tenhunen J.D., Ourcival J.M. et al., 2003. Inverse modelling of seasonal drought effects on canopy CO2/H2O exchange in three mediterranean ecosysytems, *Journal of Geophysical Research*, 108, p. 4726-4742.

Tenhunen J., Geyer R., Adiku S. et al., 2009. Influences of landuse change on ecosystem and landscape level carbon and water balances in mountainous terrain of the Stubai Valley, Austria, *Global Planetary Change*, 67, p. 29-43.

Wang Q., Tenhunen J., Schmidt M. et al., 2006. A model to estimate global radiation in complex terrain, *Boundary Layer Meteorology*, 119, p. 409-429.

Wang Q., Tenhunen J., Schmidt M. et al., 2005. Diffuse PAR irradiance under clear skies in complex alpine terrain, *Agricultural and Forest Meteorology*, 128, p. 1-15.