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Action 4 synthesis report

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CLIMFORISK

Climate change induced drought effects on forest growth and vulnerability

Data Project

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(%) of eligible costs	49.92%

Data Beneficiary

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Acronyms

Acronym	Variable name	Explanation
ET	Evapotranspiration	Flux of water vapour from forest to atmosphere. Composed of transpiration from vegetation and evaporation.
GA	Grant Agreement	Including the original study plan
GPP	Gross Primary Production	Photosynthetic CO2 uptake of forest ecosystem, i.e. the gross flux of CO2 to the forest ecosystem. When ground vegetation was excluded we refer to stand carbon budget, otherwise to forest carbon budget.
LSM	Land Surface Model	Vegetation modules used in climate models. Typically operate with coarse resolution and non-specific regional calibration.
NFI	National Forest Inventory	NFI measures a representative sample of Finnish forests annually. Information about trees and forests can be used to generate appropriate variables for e.g. model assessments of carbon balances.
NPP	Net Primary Production	Net carbon uptake of forest that is allocated into biomass. Typically NPP is 35-60% of forest GPP, while rest of the GPP is respired in metabolic processes associated with organ maintenance and growth.

Table of contents

Description of the Action 4 synthesis work in the project

The overall aim of Action 4 was to provide information about the past and future of forests in Finland, so as to provide information about growth constraints of trees in the future, as well as other background information that could benefit forest growth scenarios that can be made e.g. with MELA system that is a national forest planning tool applied in Finland (http://mela2.metla.fi/mela/julkaisut/oppaat-en.htm). To do so, we implemented carbon and water balance, and growth models of Action 3 (impact models) to climate scenarios and forest information collected in Action 2.

We produced predictions of GPP, NPP, NEP, ET, and soil moisture for a reference period based on past forest inventory data. To assess the future growth constraints of forests, we made scenarios of GPP and NPP, round-wood yield and development under set of SRES climate scenarios (CMIP3) for typical forest structures.

The importance of the assessment of uncertainties of future growth scenarios was emphasized in the GA. We wanted to take a profound look at it, and assessed the role of uncertainties stemming from i) socio-economic forcing scenario, ii) model selection, and two critical components, namely the iii) role of soil water deficit and iii) nitrogen availability for GPP and NPP development under changing climate. The latter two components were evaluated by running the impact models applying three SRES scenarios and outputs of eight climate models in each.

The main outcomes of the work conducted in Action 4 are presented in full as appendices of this report. The appendices also report the technical details of the work, while here were shortly describe the main results and conclusions stemming from the studies in more approachable format for non-experts on the matter. A short summary of the overall methodologies applied is presented in section Future forest responses are much more uncertain than what we predict for current climate conditions. This is not only due to the prognostic accumulation of errors, but due to the uncertainties associated with CO_2 responses. Water-associated uncertainties of CO_2 effects only play a role when it is dry (or excessively wet). This means that site-specific assessments accounting for topography and soil properties become ever more important for local scenario assessments, as it can determine whether e.g. droughts play a role in the future. For example, different soil water simulation schemes can easily generate large differences in year-to-year variation of productivity, as suggested by the PRELES-JSBACH comparison. Similar differences can be easily imagined to occur under climate change. Until the long-term effects of CO_2 on vegetation productivity and water use are completely resolved we suggest covering this source of uncertainty of the future, not only by covering all climate model scenarios, but also by running several impact models in parallel, and by varying assumptions of the critical components. At the same time, more research on the impacts is also needed. Currently, the impacts of climate change on nutrient availability seem to be a critical point for growth impact predictions.

The mean productivity changes obtained using outputs of eight climate models matches with earlier works (Ge et al., 2011; Kellomäki et al., 2008), but less emphasizes the role of water deficit in the future. Our work offers an additional and new view to the uncertainties of simulated growth changes. We consider that uncertainties are so large that sole treatment of the mean response is not sufficient e.g. in the MELA system. We propose implementing ensemble scenarios of growth changes, which are generated by using several climate models' outputs, and considering several impact models that predict e.g. CO2 and N effects on growth.

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Summary of the methods

Models applied

We applied the developed carbon and water balance model PRELES to draw predictions of GPP and evapotranspiration of forests, as constrained by the weather of the given simulation period. Structure of forests in simulations is either derived from forest inventory data or predetermined to a typical value, as was made in scenario simulations. Elevating CO2 increases GPP but decreases transpiration, as has been found in most empirical studies. The effects of CO2 are, however, uncertain, and there is no consensus what the due changes in GPP and transpiration are. Expected decreases of transpiration can also be offset by increasing evaporation fraction, which makes water balance predictions challenging. The detailed report of the PRELES model we developed in Action 3 has recently been published (Peltoniemi et al., 2015a) (see also Appendix M.a of this report).

Optipipe model (Valentine and Mäkelä, 2012) makes use of the prediction of GPP of PRELES by taking into consideration the nutrient dynamics of soils. The GPP of PRELES is considered as a potential and non-nutrient limited GPP. The model then finds an evolutionary founded optimal balance between carbon supply (CO2 from atmosphere) and nitrogen supplies (N from soil), which is manifested as a reiterated GPP estimate, N uptake rate, and proportions of biomasses of plant organs (allocation). The optimality assumption leads to that under elevating CO2, NPP increases can be only a fraction of potential GPP increases, biomass stock potential of forests can change, and that there can be changes in the proportions of leaves, stem wood, and roots of trees. All these could result in that the stem-wood harvest yields can be different from what can be estimated based on rules and models currently applied to forest inventory data, and applied in conventional models of stand growth.

Soil carbon model Yasso (Tuomi et al., 2011) predicts decomposition of plant residues in soil. We used this model to draw scenarios of possible long-term forest and soil carbon stock changes in the future. This model takes in the estimates of annual biomass turnover, and makes a prediction how much of the accumulated detritus carbon in the soils is released as CO2 to atmosphere annually. With constant litter input and over long time spans the carbon in soils saturates to certain dynamic equilibrium state, where the inputs and outputs of carbon from the soils are the same. As Optipipe model can be used to draw predictions of average stand biomass stock and biomass turnover under changed climate, we were able to make predictions of the changes of total forest carbon stocks under changing climate.

Materials applied

Materials applied in separate studies differed largely. The first annexed study applied the material basis created in two other studies conducted in the Climforisk project, which also evaluated their applicability and reliability (Härkönen et al., 2015; Muukkonen et al., 2015). Estimates of forest structure, i.e. the fraction absorbed radiation and species distribution were based on NFI data (10^{th} inventory cycle, with mid-year 2007)(Härkönen et al., 2015). Soil information was based on topographical map (Muukkonen et al., 2015)(see also Appendix M.d of this report).

Other two studies (climate scenario studies) did not apply measured material about forests. Rather, the scenario assessments were based on investigations of typical forests under changed climate, so that the forest structure was always the same as in the reference period.

Climate scenarios

Three emission/forcing scenarios used in these analyses were SRESB1, SRESA1B and SRESA2 (http://www.ipcc-data.org/sim/gcm_clim/SRES_TAR/ddc_sres_emissions.html). These scenarios describe the possible paths of future development of societies and the consequent emissions into atmosphere.

> SRES A1B: *A future world of very rapid economic growth, low population growth and rapid introduction of new and more efficient technology. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.*

SRES B1: *A convergent world with the same global population as in the A1 storyline but with rapid changesin economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource-efficient technologies.*

SRES A2: *A very heterogeneous world. The underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, high population growth, and less concern for rapid economic development.*

The current actual trajectory of emissions (1990 to present) corresponds mainly to A2 scenario. The projected CO_2 concentrations (parts per million, ppm) of this scenario are over 500 and 800 ppm in middle and end of this century, respectively (Figure 1). In B1 scenario, CO_2 concentration in atmosphere is almost same in middle of this century, 480 ppm, as in A2 scenario but due to rapid changes in the structures of societies, CO_2 concentration stabilizes slightly over 500 ppm. Projected annual mean temperatures of Finland in these scenarios deviate clearly from each other only during the last 30 years of the century (Figure 2). However, within one specific emission scenario the regional projections of climate models differ considerably.

The scenario climate predictions for three periods (2011-2040, 2041-2070, 2071-2100) was obtained as delta-changes relative to reference period measurements (1971-2000). Therefore, we overlaid these delta-predictions to gridded weather estimates from 1971-2000 to generate weather for scenario periods. Therefore, the weathers of scenario periods inherits similar kind of daily and annual variation as the weather of the reference period.

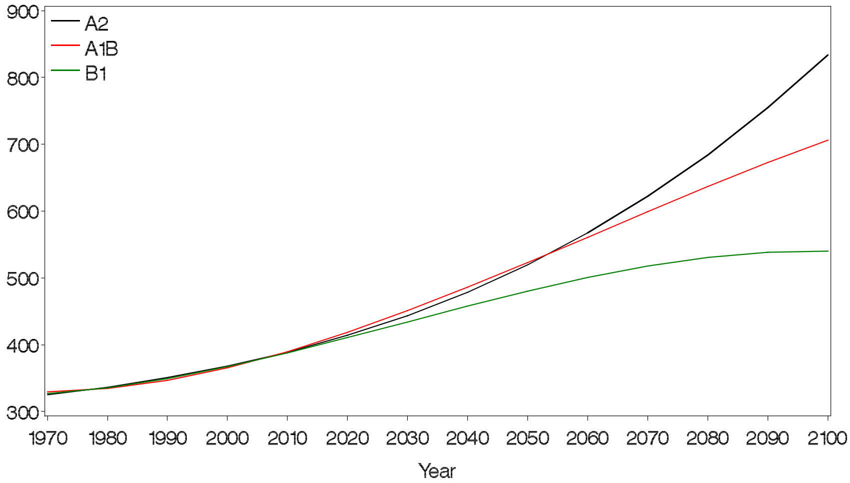

Figure 1 The development of CO2 concentration (ppm) in atmosphere over the 21st century.

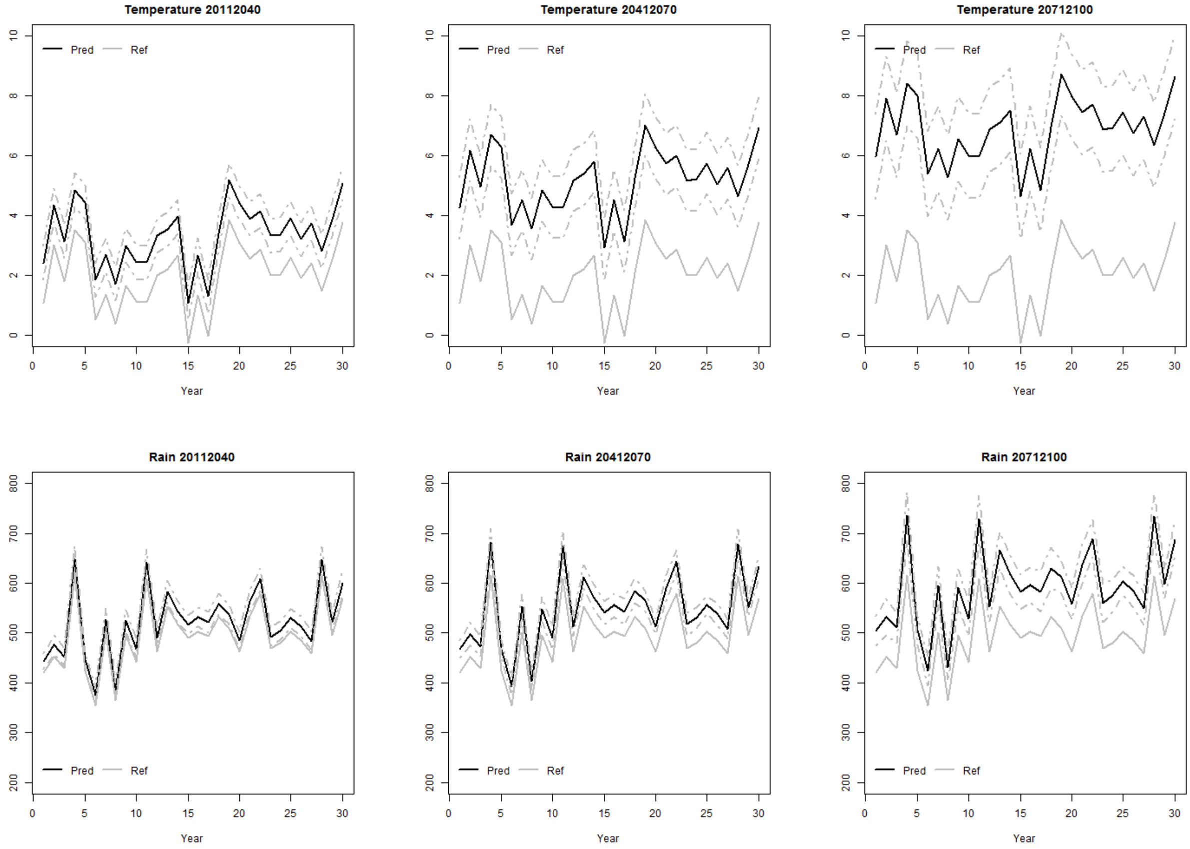

Figure 2 The development of the annual mean climate variables in SRES A2 scenario: a) Mean annual temperature, b) sum of annual precipitation. Black line is the ensemble mean (eight GCMs), dotted gray lines are ± 1 standard deviation, and gray solid line is the reference period (1971-2000) annual mean value.

Key results

Reliability of modelled reference period GPP

We devised a model inter-comparison to evaluate our model against two other~~,~~ independent ~~-~~models. The aim of the study was to find out where the models potentially go wrong, and how models should be developed further. The work was jointly conducted with the Finnish Meteorological Institute (Snowcarbo Life+ project). The entire work is reported in Peltoniemi et al. (2015b)(see also Appendix M.b of this report).

We simulated Gross Primary Production (GPP) of Finnish forests using a Land Surface Model, JSBACH, and our semi-empirical stand flux model PRELES, and compared their predictions to the MODIS GPP product. JSBACH used information about plant functional type fractions in 0.167 degree pixels. PRELES applied inventory-scaled information about forest structure at high resolution. There was little difference between the models in results aggregated to national level. Temporal trends in annual GPP were also similar. Spatial differences could be partially related to differences in model input data on soils and leaf area. Consequent to the differences in soil input data (based on topographic map in PRELES, and FAO soil map in JSBACH), and possibly due to the one-pool soil model of PRELES, PRELES was more drought sensitive than JSBACH. PRELES on the other hand, predicted drought reduction of GPP in 2006 which had exceptionally dry summer, and when GPP declined in eddy-covariance measurement of Hyytiälä site.

Differences were also detected in the seasonal pattern of GPP but they contributed only marginally to the annual totals. Both models predicted lower GPP than MODIS, but MODIS still showed similar south-north trend in GPP (**Error! Reference source not found.**).

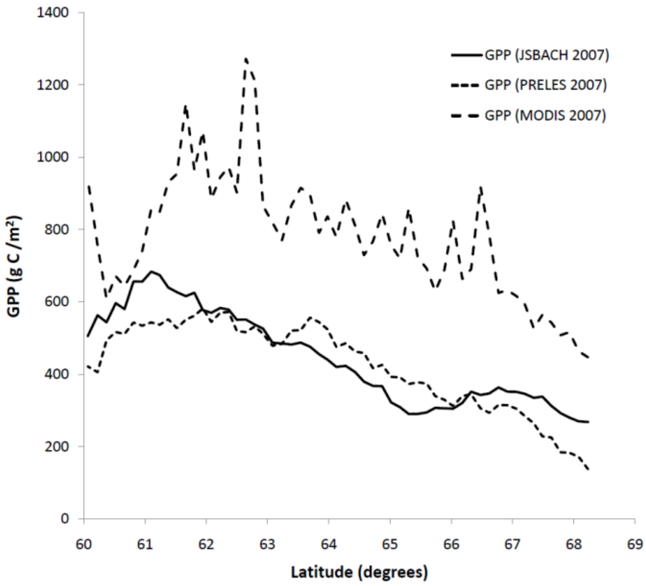

Figure 3 Comparison of mean GPP of latitudinal bins between the models.

We speculated that MODIS overestimates LAI, which produces too high GPP estimates in the boreal region although some of the differences would be explained by understorey vegetation included in the reflectances measured by MODIS. This speculation was corroborated in an assessment we carried out in another study stemming from the input data preparation for this study (Härkönen et al., 2015) (see also Appendix M.c of this report).

Our models also produced estimates of GPP in fair agreement with the estimates derived from the data used in the reporting of national forest greenhouse gas inventory of Finland to the UNFCCC. This is remarkable as all these estimates were based on different approaches, and calibration data sets~~,~~; PRELES currently calibrated with eddy-covariance data from only two sites. JSBACH parameters, on the other hand, drew from generic PFT-parameters that originated outside the study region. Consistently with previous studies (Duursma et al., 2009; Yuan et al., 2014) these findings seem to imply that the GPP process is highly generalizable, and that its calibration does not require extensive data sets.

Our study thus presented some options for further improvement of the methods:

- FAO soil map is unreliable as the basis of soil moisture simulations. It lacks spatial detail, and unlikely represents the situation of forests soils in southern Finland.
- JSBACH parameters on LAI of peat lands seem to be in need of revision.
- MODIS LAI needs to be revisited.
- PRELES could potentially benefit from layered description of soil water dynamics.
- PRELES lacked a module for deciduous phenology (added later on).

The main conclusion from our study was that we are now better informed on the methodological reliability of our approach, and it thus enhanced our confidence in reporting further model-based conclusions.

Climate change effects on GPP and NPP – lessons learned

We evaluated the sensitivity of the future gross primary productions (GPP) of Finnish forests under an ensemble of climate model projections made for three SRES emission scenarios in Kalliokoski et al., (2015) (that also appears as an Appendix M.e of this report), and under different assumptions of CO2 effect on productivity and soil moisture balance. We applied PRELES impact model, assuming unchanged forest structure and model runs on three different types of settings.

We found out that climate change projections for Finland are so radical that it is likely that the productivity of Finnish forests will increase by the end of the century. The most important determinant of the productivity increase is the CO2 fertilization effect on GPP, which is further enhanced by its negative effect on transpiration (and consequently, for more favourable soil moisture balance). Even if the CO2 effects turned out to be negligible for GPP increases in the long term, as suggested by theory of progressive nitrogen limitation (Luo et al., 2004), we would still predict increases of productivity due to increases of temperature alone, but they are small at the low extreme of climate model projections. In high emission scenario (A2), under elevate CO2, soil moisture restriction was relaxed due to increased precipitation and decreases of transpiration of trees. Again, had CO2 played a negligible role in reducing transpiration, and thus the total evapotranspiration, soil moisture deficit would have decreased the productivity more in the future than it does currently.

When applying the results on photosynthetic productivity to projections of boreal forest growth, we have to take into account that boreal forests are generally considered nitrogen limited (Tamm 1991). However, little is known about the impact of climate change on nitrogen availability in forests (Hyvönen et al. 2007, Brzostek et al. 2012). On one hand, it has been speculated that lack of nitrogen will eventually down-regulate the potential growth increases due to increased carbon supply (Norby et al. 2010), but on the other hand, the priming effect of trees on microbial activity has been claimed to provide a much larger nitrogen supply than expected otherwise (Wieder et al. 2013). Recent reports about the increasing rates of foliage and fine root turnover with increasing mean temperature (Tupek et al. 2014) also indicate that the recycling rate of nitrogen could increase largely in pace with tree growth rates, thus keeping the nitrogen supply higher. On the basis of these considerations, we constructed three contrasting yet plausible scenarios of nitrogen availability in the future. We combined this with the PRELES predictions of carbon availability, using a previously constructed growth model OptiPipe (Mäkelä et al. 2008, Valentine and Mäkelä 2012). OptiPipe is based on carbon and nitrogen balances and their optimal co-allocation so as to maximise tree growth, and is able to predict stand structural differences realistically under different nitrogen and carbon availabilities (Mäkelä et al. 2008). We simulated the model under three different SRES scenarios for spruce and pine stands in the whole of Finland. Our results indicated that NPP and woody growth will increase under climate change if N availability is also increasing. If N availability is limited, volume growth will reduce, because maintenance costs (respiration and turnover) increase. If N availability increases relatively as much or more than C availability, reduced allocation requirements to fine roots will lead to more foliage with higher photosynthetic capacity, thus increasing woody volume growth disproportionately. Importantly, the uncertainty of the growth projections due to the nitrogen assumptions was greater than that due to the climate scenarios applied.

Conclusions

Converging model estimates of national level GPP suggest that current-period vegetation-weather responses can be generated with an accuracy sufficient for climate change scenarios. Rarely, there is enough input data at very high resolutions (e.g. uncertainty of forest inventory derived data is 30-50 % at 25 m resolution) to run the impact models, so we are confined to regional assessments at best. Models are also at their best when typical or close to average forests are simulated, as there simply is not enough material for calibrating models under these conditions. For the development of models of physiological responses of trees under extreme conditions, we consider that carefully designed experiments e.g. under various drought, fertility statuses, and frosts situations should be planned.

Future forest responses are much more uncertain than what we predict for current climate conditions. This is not only due to the prognostic accumulation of errors, but due to the uncertainties associated with CO_2 responses. Water-associated uncertainties of CO_2 effects only play a role when it is dry (or excessively wet). This means that site-specific assessments accounting for topography and soil properties become ever more important for local scenario assessments, as it can determine whether e.g. droughts play a role in the future. For example, different soil water simulation schemes can easily generate large differences in year-to-year variation of productivity, as suggested by the PRELES-JSBACH comparison. Similar differences can be easily imagined to occur under climate change. Until the long-term effects of CO_2 on vegetation productivity and water use are completely resolved we suggest covering this source of uncertainty of the future, not only by covering all climate model scenarios, but also by running several impact models in parallel, and by varying assumptions of the critical components. At the same time, more research on the impacts is also needed. Currently, the impacts of climate change on nutrient availability seem to be a critical point for growth impact predictions.

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Appendices

Technical details of the work described above are in the following reports prepared in the Climforisk project.

N.a	APPENDIX_N.a_LIFE09ENV000571_Climforisk_Peltoniemi_et_al_2015a.pdf
N.b	APPENDIX_N.b_LIFE09ENV000571_Climforisk_Peltoniemi_et_al_2015b.pdf
N.c	APPENDIX_N.c_LIFE09ENV000571_Climforisk_Härkönen_et_al_2015.pdf
N.d	APPENDIX_N.d_LIFE09ENV000571_Climforisk_Muukkonen_et_al_2015.pdf
N.e	APPENDIX_N.e_LIFE09ENV000571_Climforisk_Kalliokoski_et_al_report.pdf

References

Brzostek, E. R., Blair, J. M., Dukes, J. S., Frey, S. D., Hobbie, S. E., Melillo, J. M., ... & Finzi, A. C., 2012. The effect of experimental warming and precipitation change on proteolytic enzyme activity: positive feedbacks to nitrogen availability are not universal. Global Change Biology 18.8 (2012): 2617-2625.

Duursma R.A., Kolari P., Perämäki M., Pulkkinen M., Mäkelä A., Nikinmaa E., Hari P., Aurela M., Berbigier P., Bernhofer C., and others, 2009. Contributions of climate, leaf area index and leaf physiology to variation in gross primary production of six coniferous forests across Europe: a model-based analysis. Tree Physiology. 29, 621-639.

Hyvönen R., Ågren G.I., Linder S., Persson T., Cotrufo M.F., Ekblad A., Freeman M., Grelle A., Janssens I.A., Jarvis P.G., and others, 2007. The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytol. 173, 463-480.

Härkönen S., Lehtonen A., Manninen T., Tuominen S., Peltoniemi M., 2015. Estimating forest leaf area index using satellite images: comparison of k-NN based Landsat-NFI LAI with MODIS-RSR based LAI product for Finland Boreal Environment Research. In Press.

Ge Z., Kellomäki S., Peltola H., Zhou X., Wang K., Väisänen H., 2011. Impacts of changing climate on the productivity of Norway spruce dominant stands with a mixture of Scots pine and birch in relation to water availability in southern and northern Finland. Tree Physiology. 31, 323-338.

Kalliokoski T, Mäkelä, A., Fronzek, S., Minunno, F., Peltoniemi, M, 2015, Sensitivity of gross primary production of boreal forests to climate change scenario uncertainties and tree water use efficiency. Report of the Climforisk project.

Kellomäki S., Peltola H., Nuutinen T., Korhonen K.T., Strandman H., 2008. Sensitivity of managed boreal forests in Finland to climate change, with implications for adaptive management. Philosophical Transactions of the Royal Society B: Biological Sciences. 363, 2339-2349.

Luo Y., Su B., Currie W.S., Dukes J.S., Finzi A., Hartwig U., Hungate B., McMurtrie R.E., Oren R., Parton W.J., and others, 2004. Progressive Nitrogen Limitation of Ecosystem Responses to Rising Atmospheric Carbon Dioxide. Bioscience. 54, 731-739.

Mäkelä A., Valentine H., Helmisaari H.-S. 2008. Optimal co-allocation of carbon and nitrogen in a forest stand at steady state. *New Phytologist 180:114-123.*

Muukkonen P., Nevalainen S., Lindgren M., Peltoniemi M., 2015. Spatial occurrence of drought associated damage in Finnish boreal forests: results from forest condition monitoring and GIS analysis. Boreal Environment Research. In Press.

Nevalainen S., Sirkiä S., Peltoniemi M., Neuvonen S., 2014. Vulnerability to pine sawfly damage decreases with site fertility but the opposite is true with Scleroderris canker damage; results from Finnish ICP Forests and NFI data. Ann. For. Sci., 1-9.

Peltoniemi M., Pulkkinen M., Aurela M., Pumpanen J., Kolari P., Mäkelä A., 2015a. A semi-empirical model of boreal forest gross primary production, evapotranspiration, and soil water – calibration and sensitivity analysis. Boreal Environment Research. 2.

Peltoniemi M., Markkanen T., Härkönen S., Muukkonen. P. T., T., Aalto T., Mäkelä A., 2015b. Consistent estimates of gross primary production of Finnish Forests - comparison of estimates of two process models. Boreal Environment Research. In Press.

Tamm, C. O. 1991. Nitrogen in Terrestrial Ecosystems 34–49 (Springer, Berlin).

Tuomi M., Laiho R., Repo A., Liski J., 2011. Wood decomposition model for boreal forests. Ecol. Model. 222, 709-718.

Tupek B., Mäkipää R., Heikkinen J., Peltoniemi M., Ukonmaanaho L., Hokkanen T., Nöjd P., Nevalainen S., Lingren M., Lehtonen A. 2015. Foliar turnover rates in Finland – testing needle-cohort and litterfall –biomass methods. Boreal Environment Research, in press.

Valentine H.T. and Mäkelä A., 2012. Modeling forest stand dynamics from optimal balances of carbon and nitrogen. New Phytol. 194, 961-971.

Yuan W., Cai W., Liu S., Dong W., Chen J., Arain M.A., Blanken P.D., Cescatti A., Wohlfahrt G., Georgiadis T., and others, 2014. Vegetation-specific model parameters are not required for estimating gross primary production. Ecol. Model. 292, 1-10.

Wieder WR, GB Bonan, SD Allison (2013). Global soil carbon projections are improved by modelling microbial processes. Nature Climate Change doi:10.1038/nclimate1951.

Norby R.J., Warren J.M., Iversen C.M., Medlyn B.E., McMurtrie R.E. 2010 CO2 enhancement of forest productivity constrained by limited nitrogen availability. Proc. Natl. Acad. Sci. USA 107:19368-73.

Valentine H.T, Mäkelä, A., 2012. Modeling forest stand dynamics from optimal balances of carbon and nitrogen. New Phytologist, 194, pp. 961–971.

Wieder W.R., Bonan G.B., and Allison S.D. 2013. Global soil carbon projections are improved by modelling microbial processes. Nature Climate Change Volume:3:Pages:909–912