Heathland ecosystems, human impacts and time: A long term heathland trial investigating ecosystem changes that occur after exposure to climate change, elevated N deposition and traditional vegetation management practices

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Summary

Heathland Ecosystems, Human Impacts and Time

Introduction (Chapter 1)

This series of studies on a *Calluna vulgaris* heathland focused on investigating the changes associated with environmental conditions resulting from human activities. Anthropogenic emissions of greenhouse gases have resulted in increased atmospheric concentrations of CO$_2$, CH$_4$ and NO$_x$, which has altered global temperatures through the gases absorbing outgoing radiation. Global precipitation patterns (drying trends) have been linked to these increased global temperatures. Subsequent deposition of the anthropogenic compounds back to the earth’s surface directly affects local ecosystem processes such as ecosystem species composition or soil pH. Human activities have also directly changed the land surface by vegetation management practices, which influence the rate of energy and water exchange with the atmosphere, and result in changes to C fluxes and temperature feedback patterns.

These human activities impact on our environment but they do not influence ecosystem processes independently from each other. Therefore, where possible, the investigations in this thesis linked these interactions to explain the observed results.

Investigations were undertaken at a dry heathland located at Oldebroek in the Netherlands, approximately 90 km to the north-east of Amsterdam. The *Calluna vulgaris* dominated heathland was separated into three management areas, with each area last managed (by vegetation cutting and removal) in a different year: 1984, 1993 and 2000. A long term climate manipulation trial was established on the oldest heathland community in 1998 and since then, 14 annually repeated drought treatments have been applied to the heathland community. The ecosystem is N saturated, with high bulk N and S deposition rates (10.7–37.4 kg N ha$^{-1}$ year$^{-1}$ and 4.2–6.2 kg S ha$^{-1}$ year$^{-1}$) and leaching rates (3.9–65.7 kg N ha$^{-1}$ year$^{-1}$ and 2.7–11.7 kg S ha$^{-1}$ year$^{-1}$). To the author’s knowledge, this is the first study in which multiple environmental conditions resulting from human activity have been investigated in conjunction with a long term heathland experiment.

Carbon Stocks of an Aging Heathland Community (Chapter 2)

Analysis of three ages of *Calluna vulgaris* dominated heathland indicated that the aboveground carbon allocation is associated with community age and phase of development. Aboveground Calluna carbon stock increased significantly from the Young community to the Middle community but did not significantly change from the Middle to the Old community, indicating a net carbon gain that corresponded with the growth phase
of the Calluna plants. Moss was also found to be a relatively large contributor to aboveground carbon stock (e.g. 30% in the Young community). Moss has often been excluded in aboveground assessments on Calluna heathlands which may have led to previous stock underestimation. Belowground carbon stocks to 25 cm were six to nine times greater than in the aboveground pools. Increased heathland age resulted in increased aboveground carbon stock until peak production was reached at approximately 18 years of age. However, the proportionally large belowground carbon stock eclipsed any aboveground effect when total carbon stocks were considered.

**Soil Respiration an Aging Heathland Community (Chapter 3)**

Soil respiration field data was interpreted into annual C loss predictions using modeling tools. Very few studies have reported using model selection procedures in which structurally different models are calibrated, then validated on separate observation datasets and the outcomes critically compared. This study utilized thorough model selection procedures to determine soil heterotrophic (microbial) and autotrophic (root) respiration for a heathland chronosequence. The model validation process identified that none of the six measured plant variables explained any data variation when included in models with soil temperature, which contradicts many current studies. The best predictive model used a generalized linear multi-level model format with soil temperature as the only variable. There were no heterotrophic respiration differences between the community ages. In contrast, autotrophic respiration was significantly greater on the youngest vegetation (55% of total soil respiration in summer) and decreased as the plants aged (oldest vegetation: 37% of total soil respiration in summer). Total annual soil C loss from the youngest community was estimated to be 650 g C m\(^{-2}\) year\(^{-1}\) and 435 g C m\(^{-2}\) year\(^{-1}\) for the oldest community. Understanding the C fluxes from these ecosystems provides information on the optimal management cycle-time to maximize C uptake and minimize C output.

**Soil Respiration is Suppressed by Repeated Annual Drought Conditions (Chapter 4)**

The application of 14 annually repeated droughts resulted in suppression of the total soil C loss from 392 to 332 g C m\(^{-2}\) year\(^{-1}\) (2010–11) and 427 to 358 g C m\(^{-2}\) year\(^{-1}\) (2011–12). Microbial soil respiration was the greatest contributor to heathland soil loss (74%–76%) and this was suppressed when directly exposed to drought conditions, although not significantly reduced on an annual basis. Annual root respiration was suppressed by 42% (2010–11) and 45% (2011–12) under repeated drought. The model selection process identified that soil moisture significantly improved model fit for the Drought RS data but not the Control RS data, suggesting different processes occurring between treatments. The soil moisture field observations also reflected these different processes, with greater
moisture extraction from the mineral soil by plant roots on the Drought treatment than Control. Plant activity measures did not improve the fit of any R\textsubscript{5} model, however field observations of photosynthesis (P\textsubscript{G}) showed paradoxical results, with significantly greater Drought P\textsubscript{G} than Control P\textsubscript{G}, probably associated with an increase in moss abundance. The Drought suppression of soil R\textsubscript{A} in combination with increased P\textsubscript{G} supported the hypothesis that different processes were occurring between treatments. It is proposed that these ecosystem differences were associated with changing plant characteristics, such as an increasing Drought moss cover and thickness which resulted in increased surface water holding capacity and elevated moss P\textsubscript{G}, while Calluna root systems extended deeper into the mineral soil in search of moisture.

### Ambient N Deposition Results in Soil Acidification but this is Retarded by Repeated Drought (Chapter 5)

A soil acidification trend was documented under ambient N deposition conditions over a 13 year period, suggesting that acidification continues to be a process of concern at this *Calluna vulgaris* dominated heathland with an acidic sandy soil. The annual manipulation of climatic conditions on this heathland simulated the predicted summer rainfall reduction (drought) and resulted in a long term retardation of the soil acidification trend. The pH of the soil solution significantly decreased over the course of the trial for both treatments, however, in the final two years the decline continued only in the Control treatment. This retardation is primarily associated with the reduction in rainfall leading to lower drainage rates, reduced loss of cations and therefore reduced lowering of the soil acid neutralizing capacity. However, a change in the underlying mechanisms also indicated that N transformations became less important in the Drought treatment. This change corresponded to an increase in groundcover of an air-pollution tolerant moss species and it is hypothesized that this increasing moss cover filtered an increasing quantity of deposited N, thus reducing the N available for transformation. A soil acidification lag time is expected to increase between the two treatments due to the cumulative disparity in cation retention and rates of proton formation.

### Synthesis (Chapter 6)

Human activities impact on our environment but they do not impact independently from each other. C fluxes on heathlands are influenced by drought and vegetation age and an optimum cutting frequency can be determined from the perspective of optimizing ecosystem C storage. The aboveground C storage is also affected by vegetation age, and this storage rate is likely to have been influenced by the long term N deposition that has occurred at rates exceeding critical levels. This same N deposition has resulted in a soil acidification trend, although this was retarded by the repeated annual drought.
Many of the findings were interesting and remarkable when considering the hypotheses and the results of other studies. For example, a soil acidification trend was measured even with the reduced N emissions that have been reported across Europe. Further, any C storage changes that occurred in the aboveground vegetation with increasing stand age were negligible when considering the changes to (or variability in) soil C storage. At the plot-scale, only soil temperature was found to significantly explain soil respiration (although conditional on soil moisture for the drought treatment) and measures of plant activity did not seem to influence the modeling results for total (and also therefore, root) respiration.

The modeling process also identified a number of interesting outcomes which were not directly associated with the initial soil-related hypotheses. In the course of searching for a suitable plant activity measure for soil respiration modeling, the gross photosynthesis and biomass results were used as explanatory variables. These aboveground variables showed further paradoxical results, in which drought did not reduce the C storage in the drought-plants but elevated the ecosystem photosynthetic activity. Another incidental outcome of the research was the recognition of the moss contribution to ecosystem functions such as C storage, N filtration, soil insulation (temperature and moisture) and photosynthesis. The role of mosses had previously been underestimated within the heathland.

This research has answered a number of questions about heathlands which contribute to understanding ecosystems processes at similar shrubland sites in Europe. However, this research has also raised additional questions which would benefit from further research. The major questions that have arisen are related to the possible adaptations of Calluna plants growing under annually repeated drought conditions. Why has photosynthesis increased under drought conditions? Have plants adapted to drought condition, such as changing root structures or increasing ground cover? Additional investigations into these and the other discussed processes would contribute to our understanding of the C balances of successional heathlands which are exposed to changed climatic conditions.