Impact of bioenergy production on ecosystem dynamics and services – A case study on UK heathlands

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TOC/ Abstract art

ABSTRACT. In a resource constrained world, the quest for finding alternative energy sources such as bioenergy is imperative. For sustainability's sake, the establishment of bioenergy production can no longer overlook the importance of the interactions between ecosystem and technological processes, as they must be coupled symbiotically in order to preserve ecosystem functions that provide energy and other goods and services to the human being. In this paper, a bioenergy production system based on heathland biomass is investigated with the aim to explore how a system dynamics approach can help to analyse the impact of bioenergy production on ecosystem dynamics and services and vice versa. The effect of biomass harvesting on the heathland dynamics, ecosystem services such as biomass production and carbon capture, and its capacity to balance nitrogen inputs from atmospheric deposition and nitrogen recycling were analysed. Harvesting was found to be beneficial for the maintenance of the heathland ecosystem if biomass cut fraction is higher than 0.2 but lower than 0.6, but this will depend on the specific conditions of nitrogen deposition and nitrogen recycling. When a nitrogen recycle stream was introduced in the system, biomass production was increased by up to 25% for a cut fraction of 0.4 and 95% N recycle, but at the expense of higher nitrogen accumulation and the system being less capable to withstand high atmospheric nitrogen deposition.

1. Introduction

The ever increasing world population and the aspiration for higher standards of living have imposed a grand challenge for our society: whilst demands for food, material goods and energy increase, the ecosystems that provide the resources to meet such demands are being weakened¹. Engineering research is required to seek new ways to couple ecosystem and technological processes in order to establish symbiosis that enhances resource efficiency and preserves ecosystem functions². Within a production system situated in a specific (local) ecosystem, this

may be achieved by explicitly considering the dynamics of the interacting technological and ecological components³. This allows tracking of the “provisioning” states of the system that define its capacity for meeting human needs as well as the “supporting” ecosystem states which should be maintained at a sustainable level.

In this paper, a techno-ecological system comprising a local bioenergy production based on heathland biomass is analysed, as an application of the system dynamics approach. Heathlands are an important ecosystem feature in the UK and Europe dominated by heather species (e.g. *Calluna vulgaris*), co-existing mainly with grass species (e.g. *Deschampsia flexuosa*)^{4–10}. Heathlands are a special type of moorland habitats which are currently experiencing challenges such as degradation, biodiversity loss and environmental pollution. Many audiences are looking to these areas to obtain multiple benefits including recreation and energy security but strategies for their preservation need holistic approaches to understand the effect of management practices and the interlinked social and natural processes⁸. Experimental and modelling studies suggest that increasing nitrogen (N) deposition rates alter nutrient cycling^{6,9,10}, which could trigger heathland transition into grassland^{4–10} or wooded land^{7,8}. Heathlands have often been maintained by human intervention through burning, mowing, grazing and turf cutting. Burning is a common practice for wild fire prevention, often a co-benefit from traditional moorland management for game bird rearing and sheep grazing⁸, but this practice might not be enough to keep a level of nitrogen stock in soil that preserves the heathland^{6–9}. Furthermore, with this practice the carbon and nitrogen captured by the biomass is released without any utilisation. One possible improvement could be managing a heathland in a way that a symbiotic relationship is created between ecosystem and technological processes: the growth of biomass in the heathland provides

feedstock for energy production whilst biomass harvesting helps to balance the nitrogen in the ecosystem for its preservation as a heathland.

First studies on UK heathlands have reported a net aerial biomass growth of over $10 \text{ t ha}^{-1} \text{ y}^{-1}$ for *Calluna vulgaris*¹¹. The potential of *Calluna* as a bioenergy crop in the UK has been estimated for areas under current natural conditions ($10\text{--}400 \text{ t ha}^{-1} \text{ y}^{-1}$ depending on the region and the altitude) and compared to the potential from areas already under burn management¹². Fertilisation, possibly by recycling nitrogen-rich streams from bioenergy production processes, will affect the dynamics of the ecosystem positively by increasing biomass production, and also negatively by favouring grass growth and leaching⁶⁻⁹. On the other hand, biomass harvesting can counteract the effect of nitrogen inputs due to the removal of nitrogen embedded in the biomass harvested from the heathland^{7,9}. Thus, if heathland biomass is to be harvested and used sustainably as an energy source, the two-way links between the ecosystem and technological process must be understood to assist in the selection of a level of biomass removal and nitrogen recycling that allows preservation of the heathland ecosystem while producing bioenergy output. In the present work, system dynamics modelling is used to establish the harvesting practice that potentially leads to the optimisation of bioenergy production from heathland biomass. Biomass growth models, which have been calibrated and tested using long-term field manipulation experiments^{6,11,12}, are combined with models developed for biomass conversion into heat and power. The models are then used to investigate the following aspects under various scenarios of biomass cutting and nitrogen recycling:

- The trends of stocks or states of the heathland ecosystem in terms of standing biomass, nitrogen and carbon stock

- The trends of nitrogen accumulation rates and ecosystem services such as biomass harvest rate and carbon capture rate
- The response of the system to increased atmospheric nitrogen deposition.

2. System modelling

A schematic diagram of the components, processes, flows, and states of the system analysed in this work is shown in **Figure 1**. The system comprises the air component, the heathland component, and the energy production component. The main stocks or ‘states’ are the standing biomass and the nitrogen and carbon stocks. The centre of the system is the heathland ecosystem and it is where most of the processes and flows are contained. The main biological species in the heathland biomass are heather and grass which compete for resources such as land and nutrients. The effect of energy production component on the heathland will depend on the biomass conversion technology (e.g. anaerobic digestion, direct combustion, gasification). In this work, anaerobic digestion is considered, which potentially allows for the recovery and recycling of nutrients (including particularly nitrogen) through its digestate stream. The recycling of nitrogen to the heathland and biomass harvesting from the heathland will affect the capacity of the system to retain the dominance of the heather species, while the energy production from biomass is attempted to be maximised. This compromise is analysed using the system model presented as follows. Note that all the model parameters can be found in the Supplementary Information.

Figure 1

2.1. Ecosystem component

2.1.1. Heathland biomass dynamics

The dynamics of the standing biomass state of species i can be expressed as:

$$\frac{dB_i}{dt} = G_i - M_i - H_i \quad (1)$$

102 where B_i is the standing biomass of species i in the heathland, t is time, H_i is the harvest rate,
 103 M_i is the mortality rate and G_i is the biomass growth rate. A model for the net biomass growth,

$$r_{growth,i} = G_i - M_i \quad (2)$$

104 is being used to simulate species growth of the heather *Calluna vulgaris* and the grass
 105 *Deschampsia flexuosa*¹³. The original model was transformed from a percentage land cover basis
 106 to a biomass per unit of land basis. This is essentially a Lotka-Volterra model that captures the
 107 effects of species competition and nitrogen availability on biomass growth¹³

$$\begin{aligned} r_{growth,Cal} \\ = k_{g,Cal} B_{Cal} \left(\frac{K - 0.1 B_{Cal} \alpha_{Cal} - \phi_{CD} 0.1 B_{Dsc} \alpha_{Dsc}}{K} \right) \end{aligned} \quad (3)$$

$$\begin{aligned} r_{growth,Dsc} \\ = k_{g,Dsc} B_{Dsc} \left(\frac{K - 0.1 B_{Dsc} \alpha_{Dsc} - \phi_{DC} 0.1 B_{Cal} \alpha_{Cal}}{K} \right) \end{aligned} \quad (4)$$

108 where B_{Cal} is the biomass of the heather species, kg ha^{-1}

109 B_{Dsc} is the biomass of the grass species, kg ha^{-1}

110 $k_{g,Cal}$ is the specific (net) growth rate constant of the heather in response to nitrogen, y^{-1}

111 $k_{g,Dsc}$ is the specific (net) growth rate constant of the grass in response to nitrogen, y^{-1}

112 ϕ_{CD} is the relative replacement coefficient of *Deschampsia* with respect to *Calluna*

113 ϕ_{DC} is the relative replacement coefficient of *Calluna* with respect to *Deschampsia*

114 K is the maximum percentage cover, %

115 α_i is a parameter relating percentage of cover to weight of biomass, $\% \text{ ha kg}^{-1}$

Equations 3 and 4 are models capturing competition and nitrogen effect which is not considered in the empirical Chapman correlations¹¹. The specific (net) growth rate constants are expressed as a function of nitrogen availability N_{av} (in $\text{kg ha}^{-1} \text{y}^{-1}$)¹³:

$$k_{g,Cal} = 0.01882N_{av} + 0.61203 \quad (5)$$

$$k_{g,Dsc} = 0.0275N_{av} \quad (6)$$

ϕ_{CD} is also a function of nitrogen available and can be calculated from:

$$\phi_{CD} = \frac{1}{0.016N_{av}} + 0.3 \quad (7)$$

ϕ_{DC} is equal to 1 according to¹³.

2.1.2. Nitrogen availability and nitrogen balance in soil

The nitrogen available for plant growth at a certain point in time is the sum of the nitrogen deposition, the nitrogen mineralised from plant litter in the soil and any external input such as fertilisation or nutrient recycling:

$$N_{av} = F_{dep} + F_{miner} + F_{fert} \quad (8)$$

where F_{dep} is the N deposition rate, $\text{kg ha}^{-1} \text{y}^{-1}$

F_{miner} is the mineralisation rate, $\text{kg ha}^{-1} \text{y}^{-1}$

F_{fert} is any fertilisation by, for example, recycling nutrients recovered from anaerobic digestion of soft biomass, as shown later.

The nitrogen flow from the soil due to mineralisation of nitrogen content in the plant litter can be calculated from the mortality rate constant (which is proportional to the standing biomass), the average nitrogen content and the fraction of organic nitrogen that is mineralised:

$$F_{miner} = B_{Cal}k_{m,Cal}y_{N,Cal}f_{miner,Cal} + B_{Dsc}k_{m,Dsc}y_{N,Dsc}f_{miner,Dsc} \quad (9)$$

132 where $y_{N,Cal}$ and $y_{N,Dsc}$ are the nitrogen fractions in the heather and grass, respectively; kg N
133 kg^{-1} biomass

134 $f_{miner,Cal}$ and $f_{miner,Dsc}$ are the mineralised fractions of organic nitrogen in litter from heather
135 and grass, respectively.

136 $k_{m,Cal}$ and $k_{m,Dsc}$ are the mortality and litter production rate constants of heather and grass
137 (expressed in terms of standing biomass), respectively; $\text{kg kg}^{-1} \text{biomass y}^{-1}$.

138 The balance of nitrogen stored in the soil or nitrogen state N_{soil} (kg ha^{-1}) can be written as:

$$\frac{dN_{soil}}{dt} = N_{av} + M_{Cal}y_{N,Cal}(1 - f_{miner,Cal}) + M_{Dsc}y_{N,Dsc}(1 - f_{miner,Dsc}) - N_{up} \quad (10)$$

139 where $M_{Cal} = B_{Cal}k_{m,Cal}$ and $M_{Dsc} = B_{Dsc}k_{m,Dsc}$ are the mortality rates of heather and grass,
140 respectively.

141 N_{up} is the net nitrogen uptake by the above ground standing biomass, $\text{kg ha}^{-1} \text{y}^{-1}$

142 Equation 10 assumes that any nitrogen that is not used by the plants is immobilised and
143 accumulates in the soil, ignoring losses by leaching or volatilisation. Heathlands are mostly
144 situated on well-drained soils where leaching and volatilisation occur at very low rates; therefore
145 these processes are not included in the current model¹³. Furthermore, field experiments¹⁰ have
146 shown that increases in N leaching were not observed for nitrogen deposition rates in the range
147 of $0\text{--}80 \text{ kg ha}^{-1} \text{yr}^{-1}$.

148 To calculate the net nitrogen uptake by the standing biomass, the net biomass growth rate is
149 multiplied by the nitrogen content:

$$N_{up} = y_{N,Cal}r_{growth,Cal} + y_{N,Dsc}r_{growth,Dsc} \quad (11)$$

The heathlands ecosystem services include maintenance of biodiversity, visual aesthetic, biomass production and carbon capture among others^{8,12,15,16}. The biomass supply for energy production and carbon fixation are modelled as follows.

2.1.3. Heathland ecosystem service: Biomass supply

Harvesting heathland biomass has been found feasible using mowers and other adapted machineries such as the bio-baler consisting of mulcher and baler¹⁵. Successive annual harvesting over the entire heathland is assumed. Cut fraction, representing the mass fraction of the total biomass available at certain point in the heathland, is used as a parameter to capture the effects of different harvesting rates.

The biomass harvesting rate is calculated from:

$$H_i = B_i \times f_{cut} \quad (12)$$

where H_i is the harvested biomass yield of species i , $\text{kg ha}^{-1} \text{y}^{-1}$

f_{cut} is the annual cut fraction, assumed to be the same for both plants, y^{-1}

The total biomass flow rate supplied from the heathland ecosystem is calculated as:

$$F_h = (H_{cal} + H_{Dsc})A_h \quad (13)$$

where F_h is the total harvested biomass flow rate kg y^{-1}

A_h is the harvested area, ha

2.1.4. Heathland ecosystem service: Carbon capture

The main carbon input to the heathland ecosystem is the CO_2 that is fixed by growth. The output flows include the carbon in harvested biomass and carbon losses from the soil stock to the atmosphere. Carbon is captured by the ecosystem due to biomass growth and the carbon accumulation in soil due to litter production. The carbon lost to the atmosphere is dependent on the carbon stock in soil. The carbon balance in the soil can be written as:

$$\frac{dC_{soil}}{dt} = (M_{cal} + M_{Dsc})y_C - C_{soil}k_{lossC} \quad (14)$$

where y_C is the carbon fraction in the biomass, kg C kg^{-1}

C_{soil} is the carbon stock in soil, kg ha^{-1}

k_{lossC} is the soil C loss rate constant, y^{-1}

It is recognised that there are various components to carbon losses but the model is at the moment limited by data availability and does not distinguish carbon species or lateral losses through the fluvial system. This is an initial model used to illustrate the importance of analyzing techno-ecological interactions but it can be extended to include factors or details not currently represented.

The carbon capture rate by the heathland ecosystem can be calculated from:

$$F_C = \sum_i \left(\frac{r_{growth,i}}{f_{AG,i}} \right) y_C + \frac{dC_{soil}}{dt} \quad (15)$$

which can be combined with equation 14 to give

$$\frac{dC_{(s+b)}}{dt} = F_C = \sum_i \left(\frac{r_{growth,i}}{f_{AG,i}} + M_i \right) y_C - C_{soil}k_{lossC} \quad (16)$$

where $\frac{dC_{(s+b)}}{dt} = F_C$ is the total carbon capture rate by the heathland ecosystem in the soil and biomass prior to harvesting, $\text{kg ha}^{-1} \text{y}^{-1}$.

$f_{AG,i}$ is the fraction of biomass growth allocated to above-ground biomass of species i . Thus

$\frac{r_{growth,i}}{f_{AG,i}}$ is the total net growth from both above-ground and below-ground biomass.

Since the carbon fixed in the harvested biomass will be converted into CO_2 after energy production, the net carbon capture rate by the managed heathland ecosystem is:

$$F_C^{net} = F_C - F_h y_C \quad (17)$$

In addition to carbon capture, carbon emission reduction due to the displacement of fossil fuels by the use of biomass in energy production can be estimated, as shown in the Supporting Information.

2.2. Energy production component

The biomass is assumed to be converted into heat and power as shown in **Figure 1**. The possibility for separation of the biomass feedstock into woody biomass and soft biomass (leaves, flowers, green shoots) is considered¹⁵. The woody biomass is combusted for combined heat and power (CHP) generation. The soft biomass is sent to anaerobic digestion (AD) which generates biogas for CHP and produces digestate allowing nutrient recovery. The nutrients can be recycled back to the heathland or exported to another system.

Anaerobic Digestion

The soft biomass is sent to anaerobic digestion to produce biogas. The biogas production rate is estimated by:

$$F_{Biogas} = F_{SB} y_{VM} Y_{biogas} \left(y_{CH_4} \times \frac{16}{22.4} + y_{CO_2} \times \frac{44}{22.4} \right) \quad (18)$$

where

F_{Biogas} is the biogas flow rate, kg y⁻¹

F_{SB} is the soft biomass feedstock flow rate (see **Supporting Information**), kg y⁻¹

y_{VM} is the volatile matter (VM) content in the feedstock, kg VM kg⁻¹

Y_{biogas} is the biogas yield, m³ biogas kg⁻¹ VM

y_{CH_4} and y_{CO_2} are the volumetric fractions of methane and CO₂ (with $y_{CO_2} = 1 - y_{CH_4}$ if other components' fractions are negligible)

207 From the mass balance of nitrogen in the AD unit with f_{Nloss} denoting the fraction of nitrogen
 208 lost in the gaseous stream, the remainder of the nitrogen which leaves with the digestate can be
 209 calculated by:

$$F_{N,dig} = (y_{N,Cal}H_{Cal}f_{soft} + y_{N,Dsc}H_{Dsc})(1 - f_{Nloss})A_h \quad (19)$$

210 The amount of nitrogen recycled is varied by introducing a recycling fraction (f_{Nrec}) as
 211 parameter:

$$F_{Nrec} = F_{N,dig}f_{Nrec} \quad (20)$$

212 *CHP production*

213 The heat and energy production from CHP plant can be estimated from the following
 214 equations

$$F_{el} = \frac{F_{fuel} \times HV_{fuel} \times \eta_{el}}{1000} \quad (21)$$

$$F_{heat} = \frac{F_{fuel} \times HV_{fuel} \times \eta_{th}}{1000} \quad (22)$$

215 where F_{fuel} is the annual flow rate of the fuel used in the CHP plant, kg y⁻¹ or m³ y⁻¹

216 F_{el} and

217 F_{heat} are the electricity and heat production from the CHP plant, respectively, GJ y⁻¹

218 HV_{fuel} is the heating value, MJ kg⁻¹ or MJ m⁻³

219 η_{el} and η_{th} are the electrical and thermal efficiency of the CHP plant, respectively

220 The fuel can be the woody biomass, or the biogas produced from AD of soft biomass. The
 221 energy conversion efficiencies assumed are presented in the **Supporting Information** along
 222 with the values of the other parameters in the model presented above.

The model has been used to estimate the potential for bioenergy production and the effect on the ecosystem maintenance and services of heathland areas around the Whitehill and Bordon eco-town in Hampshire, UK^{15,17}. The model was solved using the Runge-Kutta method using the model parameters shown in the Supporting Information. Initial conditions and local parameters are summarised in **Table 1**. The initial conditions were assumed as of the heathland following intensive burning on-site which reduces both the standing biomass as well as the litter layer. The values used in the case study are considered as close to those used in reference¹³, but these values can vary widely depending on the specific case under study.

Table 1

3. Results and discussion

3.1. System with no nitrogen recycle

The system was analysed with the current nitrogen deposition value at the locality of Whitehill and Bordon as the only nitrogen input (shown in **Table 1**). **Figure 2** shows the trends of the standing and harvested biomass and nitrogen stock in soil for two different cut fractions. **Figure 2a** shows that with a cut fraction of 0.2 the heather initially dominates until heather biomass reaches a maximum and then declines. The grass biomass increases steadily and eventually becomes dominant. Under this regime, the heathland might become grassland in the long term. The impact of biomass cutting in maintaining the ecosystem is shown in **Figure 2b**. Comparing **Figure 2a** and **Figure 2b**, one can see that as cut fraction is increased from 0.2 to 0.4, the heather is able to over compete grass and reach a steady state where it remains as the dominant species. Furthermore, nitrogen stock in soil is also reduced. This is mainly because less biomass is left standing and then less litter is produced whilst more nitrogen uptake is required for the standing plus harvested biomass. It can be observed that the ratio between the heather and the grass biomass is highly impacted by the cut fraction and thus the harvesting of the grass together with

the heather with a proper cut fraction helps to maintain the heathland. Figure 2 also shows that carbon stock declines when grass takes over heather at a low cut fraction (Figure 2a), but it is enhanced when heather stays as dominant species at a higher cut fraction (Figure 2b).

Figure 2

Figure 3 shows the steady state results of the system states and ecosystem services. At steady state the harvesting rate is equal to standing biomass growth rate, thus $r_{growth,i} = H_i$ indicates at which rate the ecosystem can provide biomass steadily for energy production for each cut fraction. Note that the values for other state variables and rates in the system correspond to this point, i.e. where biomass growth and harvesting are balanced. According to **Figure 3a**, $f_{cut}=0.4$ allows the highest heather biomass harvest without triggering its conversion into grassland or falling into a depleting regime. The ecosystem enters into a depleting regime when the biomass harvest rate is greater than biomass growth, as shown for $f_{cut} \geq 0.6$. This ecological limit set by the ecosystem dynamics is to be observed by the technological process, so that its design exploits the ecosystem service of biomass production in a sustainable manner.

Examining carbon capture by the heathland, **Figure 3a** shows that the optimal cut fraction for this ecosystem service ($f_{cut}=0.25$) is not necessarily the same as that which allows the highest biomass harvest ($f_{cut}=0.4$). Looking at the impact of cut fraction on the stocks, **Figure 3b** shows that the highest standing heather biomass stock and the highest carbon stock coincides with the highest carbon capture rate. At around $f_{cut}=0.25$ the heather starts becoming dominant, which produces a peak in carbon capture rate due to a peak in standing heather biomass. However, the carbon capture rate then declines as cut fraction increases since lower biomass stock is left in the heathland. The carbon capture rates combined with the avoided carbon emissions due to displacement of equivalent amounts of energy production are also shown in **Figure 3a**. As it can

be observed, the reduction in carbon capture rate is compensated by the carbon avoidance due to displacement of fossil-based energy by the biomass-derived energy.

Figure 3

The standing biomass at steady state (reached after more than 10 years) range from 6 to 12 t ha⁻¹, which is comparable to results from empirical studies for natural succession (around 8 t ha⁻¹ after 10 years)¹¹, and for a field under burn management and similar N deposition level (10 t ha⁻¹ after 210 years)¹⁰, and for mowing management under similar N deposition (8-15 t ha⁻¹ in 15-year cycle)⁶.

3.2. System with nitrogen recycle

To illustrate the effect of nitrogen recycle on biomass production, standing and harvested biomass have been plotted in **Figure 4** for a recycle of 50% of the nitrogen in the soft biomass. The dynamic trends are similar to those without nitrogen recycle (**Figure 2**) but more biomass is produced in the case with nitrogen recycle. **Figure 5** shows steady state results. **Figure 5a** and **5b** show that the amounts of biomass that can be harvested, the carbon capture and nitrogen accumulation rates are higher than in the case without nitrogen recycle (**Figure 3**). **Figure 5c** shows that as the nitrogen recycle increases the system requires more intensive biomass harvesting (i.e. higher cut ratio) in order to enable the ecosystem to be maintained as a heathland. **Figure 5d** shows that the higher the recycle rate, the higher the nitrogen stock in soil.

Figure 4

Figure 5

Figure 3a and **Figure 5d** show that the heathland features higher nitrogen accumulation rates at low cut fractions. Note that the highest nitrogen stock in soil occurs around the values for which the carbon capture rate, standing biomass and carbon stock are the highest. Thus, if the system is

operated considering only the latter three criteria the soil may become saturated with nitrogen, leading to ecosystem instability and significant levels of nitrogen leaching to water and volatilisation to air^{4,5,10}. Thus, the trade-off between carbon and nitrogen accumulation rates needs to be considered. **Figure 6a** illustrates this trade-off at various cut fractions in terms of the ratio of carbon capture rate to nitrogen accumulation rate. Analysing the system without nitrogen recycle, the best trade-off is obtained at $f_{cut}=0.4$. At this point the highest mass of carbon is being captured per unit of nitrogen mass accumulated. As shown in **Figure 3a**, this is at the expense of carbon capture rate being lower than the highest possible but still maintained at relatively high levels. Two major benefits are obtained at $f_{cut}=0.4$: the ecosystem is maintained at relatively low nitrogen levels (one of the objectives of heathland management) and the biomass provisioning service is at the highest flow rate. This also exemplifies that information derived from analysis of system dynamics can support decision making with a view to establish symbiotic interactions between ecosystem and man-made energy production system. In the cases with nitrogen recycle, **Figure 5a** shows that the cut fraction corresponding to the best trade-off can change with the nitrogen recycle rate. The best trade-off is obtained at $f_{cut}=0.4$ for nitrogen recycles of 10% and 50%. For nitrogen recycle of 95%, the best trade-off occurs at $f_{cut}=0.5$. These cutting fractions are relatively lower than burning management, which typically removes around 70% (i.e. $f_{cut}=0.7$) of the biomass²⁰. The standing biomass (Figures 3b and 5c) can also be compared with that for mowing at $f_{cut}=0.65$ ($\sim 5 \text{ t ha}^{-1}$), burning at $f_{cut}=0.7$ ($\sim 4 \text{ t ha}^{-1}$) and sod cutting at $f_{cut}=1$ ($\sim 7 \text{ t ha}^{-1}$)⁷.

Figure 6

3.3. System response to increased nitrogen deposition rate

From the previous results, the combination of high nitrogen recycle (e.g. 95%) and cut fraction ($f_{cut}=0.5$) appeared to be favourable for the sustainable production of heathland biomass for

bioenergy purposes, assuming all other variables remain unchanged. However, the ecosystem might be less resilient to external and uncontrolled effects from the environment such as a change in the atmospheric nitrogen deposition. **Figure 6b** shows the effect of nitrogen deposition on the standing heather biomass at steady state for each nitrogen recycle percentage, with the cut fraction fixed at 0.5. It can be observed how at higher nitrogen recycle rates the capability of the system to reach a stable state with heather as dominant species is reduced. At 0% (i.e. no nitrogen recycle) and 10% nitrogen recycle, the system can bear nitrogen deposition of up to 35 kg ha⁻¹, before heather biomass starts a declining trend. This limit is reduced to 20 kg ha⁻¹ when the system recycles 60% or more of the nitrogen content in the harvested soft biomass. Thus, depending on the nitrogen deposition predictions, the level of nitrogen recycle should be set accordingly to maintain the durability of the whole system.

3.4. Implications for the functioning of the heathland and bioenergy production system

Table 2 shows the evaluation of the functioning of the ecosystem and the bioenergy production system in various aspects, with simulation results based on (1) the cut fractions yielding the best trade-off between carbon capture and nitrogen accumulation in soil, and (2) the corresponding nitrogen recycle percentages. The energy production at steady state increases with nitrogen recycles and cut fraction but at the expense of a lower limit for the nitrogen deposition rate that the heathland is able to balance effectively in order to maintain the ecosystem. Note that 50% and 95% nitrogen recycle achieve similar carbon capture in soil and uncut standing biomass and avoided carbon emissions due to displacement of energy from fossil fuels. It was estimated that between 17 and 25% of the total electricity demand by the Whitehill and Bordon eco-town along with between 5 and 7% of the total heat demand could be satisfied from the management of 1600 ha of heathland available. This equates to supplying between 80 and 100% of electricity and between 28 and 42% of heat demand to the new 4000 houses planned for the eco-town

redevelopment; displacing the equivalent amount of energy from grid electricity and natural gas shown in Table 2.

Table 2

The integrated modelling allowed capturing the mutual impact between the dynamics of the ecosystem processes in a heathland, such as biomass growth and competition and uptake of nitrogen inputs, and the performance of the energy production system. The biomass growth depends on the nitrogen inputs and standing biomass of the vegetation species, and affects the availability of feedstock for heat and electricity production. At the same time, the energy conversion component consisting of anaerobic digestion and combined heat and power allowed to recycle some nitrogen back to the heathland ecosystem as long as it promotes the desired growth of biomass and avoids the shift of the system from heathland to grassland. When the system is well maintained via the selection of cut fraction and nitrogen recycle percentage, it shows the potential to deliver simultaneously both the function of biomass production and that of carbon fixation. Overall, the modelling results highlight the usefulness of dynamic modelling for supporting long-term policy and industrial decisions to ensure the whole production system can be run in a sustainable manner.

FIGURES

Figure 1 Techno-ecological system for bioenergy production from heathland biomass

Figure 2 Trends of standing and harvested biomass and nitrogen in soil for a heathland under atmospheric deposition of 16 kg N ha⁻¹ y⁻¹, and annual cut fraction of a) 0.2 and b) 0.4

Figure 3 a) Biomass, carbon and nitrogen rates and b) stocks in the heathland ecosystem at various cut fractions for the system without nitrogen recycle.

Figure 4 Dynamic trend of a) standing and b) harvested heather biomass at different annual cut fractions (f_{cut}) and under atmospheric deposition of $16 \text{ kg N ha}^{-1} \text{y}^{-1}$ and 50% recycle of the nitrogen in the soft biomass.

c)

d)

Figure 5 a) Heather biomass harvest, b) carbon capture and nitrogen accumulation rates, c) heather biomass stock and d) carbon (C) stock (in soil and standing biomass) and nitrogen (N) stock (in soil) under different values of annual cut fraction and nitrogen recycle.

a)

b)

Figure 6 a) Trade-offs between carbon capture and nitrogen accumulation rates and b) ecosystem response to nitrogen deposition under different scenarios of nitrogen recycle (N rec) in terms of standing heather biomass.

TABLES

Table 1 Initial conditions and local parameters

Initial conditions				Source
Initial	heather	200	kg ha^{-1}	Assumed

biomass			
Initial grass biomass	50	kg ha ⁻¹	Assumed
Initial N in soil	10	kg ha ⁻¹	Assumed
Initial C in soil	350	kg ha ⁻¹	Assumed
Local parameters			
Population	16917	person	17
Harvested heathland area, A_h	1600	ha	15
N deposition, F_{dep}	16	kg ha ⁻¹ y ⁻¹	18
Electricity demand	9.11	GJ/person	19
Heat demand	40.3	GJ/person	19

385 Table 2 Summary of results for the combinations of nitrogen recycle percentage and cut fractions
386 for the best trade-off between carbon capture and nitrogen accumulation in soil.

Nitrogen recycle	f_{cut} for best trade-off	Electricity production at SS (GJ y ⁻¹)	Heat production at SS (GJ y ⁻¹)	% of the local heat demand supplied from heathland at SS	% of the local electricity demand supplied from heathland at SS	C captured + avoided C emissions after 50 years (t ha ⁻¹)	Nitrogen deposition limit (kg ha ⁻¹ y ⁻¹)
0	0.4	36860	46350	17.0	4.8	120	35
10%	0.4	38250	48100	17.6	5.0	125	35
50%	0.4	42700	53700	19.7	5.6	140	30
95%	0.5	53900	67800	24.8	7.1	146	20

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388 ASSOCIATED CONTENT

Supporting Information. Model parameters and auxiliary equations. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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