POTENTIAL OF THE DAYCENT MODEL TO PREDICT CHANGE IN GREENHOUSE GAS EMISSIONS WITH CESSATION OF TILLAGE FOR CULTIVATION OF PERENNIAL ENERGY CROPS

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Abstract

Bioenergy may make up a significant proportion of future renewable energy supplies, and for perennial feedstocks, this will require conversion of land to a no till (NT) system. Previous studies suggest that NT leads to increased soil organic matter (SOM) storage, which breaks down over time resulting in increased N_2O emissions. This may not indicate net total increase, since indirect emissions from eroded SOM with tillage should be considered. Given the high global warming potential of N_2O, it is crucial to predict net change in emissions rather than focusing only on potential for C storage. The DayCent model has been used to represent both tilled [1, 2], and untilled [3, 4] agroecosystems. This study assesses its suitability to represent land conversion to NT; first by exploring model structure and process representation, and secondly by using sensitivity analysis to identify whether DayCent matches published variation between tillage regimes.

DayCent predicts increasing surface and slow-decomposing soil carbon for no till, but not the expected increase in N_2O emissions. It has been suggested that changes in soil structure with tillage affect infiltration, and therefore nitrification and denitrification processes leading to N_2O emissions [5, 6]. For accurate simulation of the relationship to precipitation, DayCent should ideally represent differing soil water capacity (SWC) and porosity between tillage regimes, and the impacts on water filled pore space (WFPS). DayCent also fails to appropriately respond to low C:N ratio residue applications, or to simulate interaction between tillage and nutrient applications. Recommendations are provided for improvements to DayCent to resolve these issues and enable more robust scenario analysis. Assuming improved performance at validation, this should facilitate more accurate carbon equivalent emissions for land use change, incorporating N_2O.

Keywords: perennial crops, bioenergy, mechanistic modelling, N_2O, macroporosity

Introduction

Climate change, attributed to greenhouse gas (GHG) emissions from fossil fuel use, creates a need for renewable, low carbon energy sources, driving a potential increase in energy crop cultivation [7-9]. As one of few non-intermittent renewables, biomass is often promoted as base load electricity supply. Theoretical potential for bioenergy could meet the IPCC estimate of 1000 EJ yr^{-1} energy demand for 2050, although less than 96 EJ yr^{-1} of bioenergy is available from waste and residues, and competition with food crops must be taken into account when considering potential cultivation of feedstock [10-12].

Fertilisers applied to crops may be produced from fossil fuels, require energy to produce and apply, and can generate N_2O emissions from soil [13, 14]. Cultivation of perennial feedstocks such as willow and *Miscanthus* often requires lower agrochemical inputs than cultivation of annuals such as corn, thus promising lower GHG emissions and higher net energy generation [15-17]. Depending on location, perennial cultivation may require conversion of managed land to a no till (NT) system. Factors influencing land conversion may be socioeconomic as opposed to agricultural, with farmer choice, feedstock supply chains and profitability controlling locations of cultivation [18, 19].

Since GHG mitigation is identified as a key aim of bioenergy, it is crucial to consider the GHG balance of associated land use change. For example, land use change for cultivation of palm biodiesel on former peatland rainforest would generate 0.1 mg/m^2 CO_2, with 50% of carbon losses from below ground [20]. Perennial no till (NT) systems protect and stabilise soil, and there is less redistribution of organic matter and aeration of soil to encourage decomposition, meaning that below-ground carbon storage may exceed annual arable ecosystems and equal some forest and grassland systems, although time taken to reach equilibrium and repay carbon debt from disruption must be considered [15, 20-22].

Numerous field studies have identified an increase in N_2O emissions in the years immediately following cessation of tillage [5, 23]. This increase may be offset by a decrease in indirect emissions from eroded soils, or may reflect an increase in rates of denitrification due to structural changes to the soil [23-25].

The global warming potential of N_2O is 298 times that of CO_2, and agriculture contributes 58% of anthropogenic N_2O emissions, making up 10-12% of total anthropogenic GHG emissions [26-28]. Agricultural N_2O emissions are often calculated by multiplying N fertiliser applications by an emissions factor; although soil type, precipitation regime and other management practices should also be considered [29, 30]. Soil management can contribute significantly, for example, the Land Use, Land Use Change and Forestry method estimates average emissions of 7.4 Gg/yr N_2O due to disturbance of soils with land use change in the UK from 1991-2005 [31].

Therefore, prediction and assessment should take place before land use change, and should factor in total agroecosystem change, not just fertiliser application, and must consider both direct and indirect emissions of N_2O and CO_2, in order to ensure bioenergy cultivation has beneficial GHG balance. The DayCent model could be applied in such an assessment, as it has been used to represent both tilled [1, 2], and untilled [3, 4] agroecosystems. This study assesses the model's suitability to represent land conversion to NT.

Assessment of field studies

Change in land management and resultant changes in soil structure may affect nitrification and denitrification, resulting in a change in proportional rate of loss of N from soil, which may compound or counterbalance change in emissions due to change in soil N [24]. An apparent lack of consensus in N_2O field emissions response to NT has been highlighted by previous comparative assessment [32]. This variation may reflect differing time since conversion, soil organic matter (SOM), texture, precipitation regime, crop and cropping schedule, and other management effects (e.g. OM inputs etc). Soil structural changes with conversion to NT will have different impacts according to these properties, due to interaction of site factors such as soil and climate with management factors such as tillage. Table 1 compares data from the literature.

Table 1: Variation in response to NT, according to soil type and crop.

Increase in N_2O emissions under NT	Decrease in N_2O emissions under NT
Heavy clay, barley, 3-5 yrs post till [33]	Sandy loam, perennial vs annual crops [29]
Review of literature on field measurements for both humid and dry climates, mostly in the U.S. (decrease for humid climates after 20 years) [5]	Clay loam, soy [34]
Clay, barley [35]	Clay, rice and signal grass rotation [36]
Clay, silt, loam and organic soils, barley [37]	Poorly drained clay loam, arable rotation [38]

N_2O emissions from soils are mostly a product of microbial nitrification and denitrification, with denitrification often regarded as the primary mechanism. Denitrification is an anaerobic reduction process, prolific in waterlogged anoxic soils, with N_2O produced as an intermediate, accounting for around 5% of the end product, [24, 39, 40]. N_2O emissions are highest around 60% WFPS; at lower levels denitrification is less common, and at higher levels completion of reactions to produce N_2 is more likely [41]. Soil structure and organic matter affect soil oxygen status, water storage and movement, microbial community and nitrogen availability, and thus control rates of N_2O production.

Studies in Table 1 which identify increase in field emissions of N_2O under NT cite a decrease in porosity, and associated increase in percentage water filled pore space (WFPS) and reduction in drainage, leading to reduced O_2 diffusivity, and increased tendency for anoxic conditions, suitable for denitrification [5, 33, 35, 37]. Tillage increases porosity over the affected depth, whilst compaction from precipitation, freeze-thaw settling, or traffic may reduce porosity; severity of compaction may increase at higher organic matter content, and inter-aggregate pores are more easily lost than textural pores [42, 43]. As a result, porosity tends to be lower for NT soil, and may decrease under time with since tillage.

Decrease in field emissions of N_2O under NT has been attributed to higher levels of available N in tilled soil: since tillage aerates soil and redistributes surface residues to more microbially active layers, decomposition and release of N within soil are increased [34, 36]. Tillage also breaks down aggregates, making organic matter more physically available for decomposition [44]. Another study [29] cited higher WFPS for NT as the cause of decreased N_2O emissions, since study conditions favoured nitrification as the main N_2O production mechanism. Surface residues may have a cooling effect on NT soil, and lower temperatures may mean slower rates of microbial processes [38]. Residues also protect soil from aggregate breakdown by precipitation, erosion, surface crusting and splash infilling of macropores [45].

Soil porosity changes due to tillage regime may be less important for soils with good drainage or high evaporation from surface layers, which may explain some variation in findings for field studies [36].Six *et al*. [5] attribute reduction for humid climates after 20 yrs to excessive denitrification rates causing N store exhaustion, which highlights the dangers of comparing tillage conditions without taking into account longevity prior to study.

Structural changes such as macroporosity and organic structure may also be significant. Macropore connectivity affects flow of water through soil, impacting both on leaching (affected by flow rate and contact with soil matrix N) and soil pore water: vertical channels are particularly important [46]. Macropore connectivity is disrupted by tillage, and builds over time with root channels, and vertical fracturing or burrowing [24, 47]. Organic matter also contributes to structure, and correlates with porosity, soil water capacity (SWC), soil water retention and aggregate stability [48-52]. Increase, or stratification of soil carbon under no till will therefore affect soil water profile, and anoxic conditions may increase near the surface where SOM is concentrated [53]. Since gases produced in surface layers have less distance to escape, this may increase N_2O emitted. Aggregate size is also a control; when structural pores have low WFPS, aggregates may still contain anaerobic zones favourable for denitrification; in contrast under anoxic conditions, aggregate size has been found to correlate negatively with N_2O and CO_2 emissions [44, 54, 55]

Process representation in DayCent

The assessment of field studies above identified impacts on denitrification rates from: soil porosity, aggregate stability, soil C and N, SOM distribution, decomposition (and associated oxygen consumption), macropore connectivity and soil water holding capacity. Key controls on rates of N_2O production are therefore identified as soil oxygen status and N availability, and factors affecting both must be represented for good prediction of potential change in emissions. The following table identifies general capabilities of DayCent to represent these variables, and their change over time; where a variable is updated at each timestep, it can more easily be adapted to represent impacts of variation in tillage regime.

Table 2: Capabilities of DayCent to represent change in agroecosystem properties over time.

Soil property	DayCent representation
Soil porosity	Calculated from bulk density. Bulk density is based on soil grain size distribution. This value is constant.
Aggregate stability	No representation.
Soil erosion	Erosion events need to be scheduled manually, giving input of soil loss in kg/m: depth lost is calculated according to bulk density, with no computation of impact of crop or management type.
SOM distribution	Soil model updates SOM for individual layers over time.
Decomposition and oxygen consumption	Variation in reaction rates with temperature and WFPS over depth is accounted for.
Macropore connectivity	Porosity is represented only as an average value per layer, based on grain-size distribution, there is no representation of macropore networks or their variation with time.
Soil C and N	Soil C and N are recalculated according to inputs and transfers between soil pools at each timestep.
SWC	Set at the start using input data, or calculations based on user input data for grain-size distribution and organic matter.
Soil water flow	DayCent uses a single porosity representation of water flow, which is unable to represent the impacts of changes in aggregate size or macropores on flow dynamics.

The expected increase in N_2O emissions under NT has been attributed to structural changes, or C-N coupling [5, 23]. Impacts of tillage are represented in DayCent by two key mechanisms: a factor is applied for 1 month, to increase decay rates and transfer between SOC pools after tillage; and microbial yield efficiency is increased [56-58]. As such, the only aspects of variation between tillage systems which are represented are decomposition rates and carbon pool transfers, and there is no representation of porosity changes controlling WFPS. Thus, the model is only able to represent the aspects of no till which promote reduction of N_2O emissions, and not the aspects which promote increased emissions.

Porosity is made up of textural (within aggregates) and structural (between aggregates) pores; structural pores may include long connected worm/root channels, as well as inter-aggregate voids. Porosity is currently represented in DayCent using an average value. There is a spectrum of approaches to represent textural and structural pores separately, which would add varying degrees of complexity to the model: to minimise this, an approach requiring only one additional parameter could be applied, by splitting hydraulic conductivity for macropores and matrix pores [47, 59]. Useful dual porosity representation should include variation in N between matrix water and macropore water, with N exchange according to relative rates of macropore flow and diffusion; this would add significant further complexity to the model [47]. These changes would enable representation of structural factors such as aggregate size and macropore connectivity which directly affect N_2O emission rates; however there is no consensus on prediction of variation in these factors over time, or with tillage [60]. Improving representation of porosity and structure may therefore not be worthwhile.

DayCent model output

The assessment of field studies above highlights an increase in WFPS under NT conditions, which often leads to increased N_2O emissions (where denitrification is the primary production mechanism) unless this effect is countered by lower temperatures or lower N availability in the NT soils. It is also suggested that an increase in WFPS may be less significant for well drained soil, or where evaporation is high. Hence DayCent should represent increased N_2O emissions for NT of poorly drained soils, but may represent the reverse or no difference where one of the listed mitigating factors is relevant. This study therefore performed sensitivity analysis to identify whether DayCent predictions are as expected for these variables.

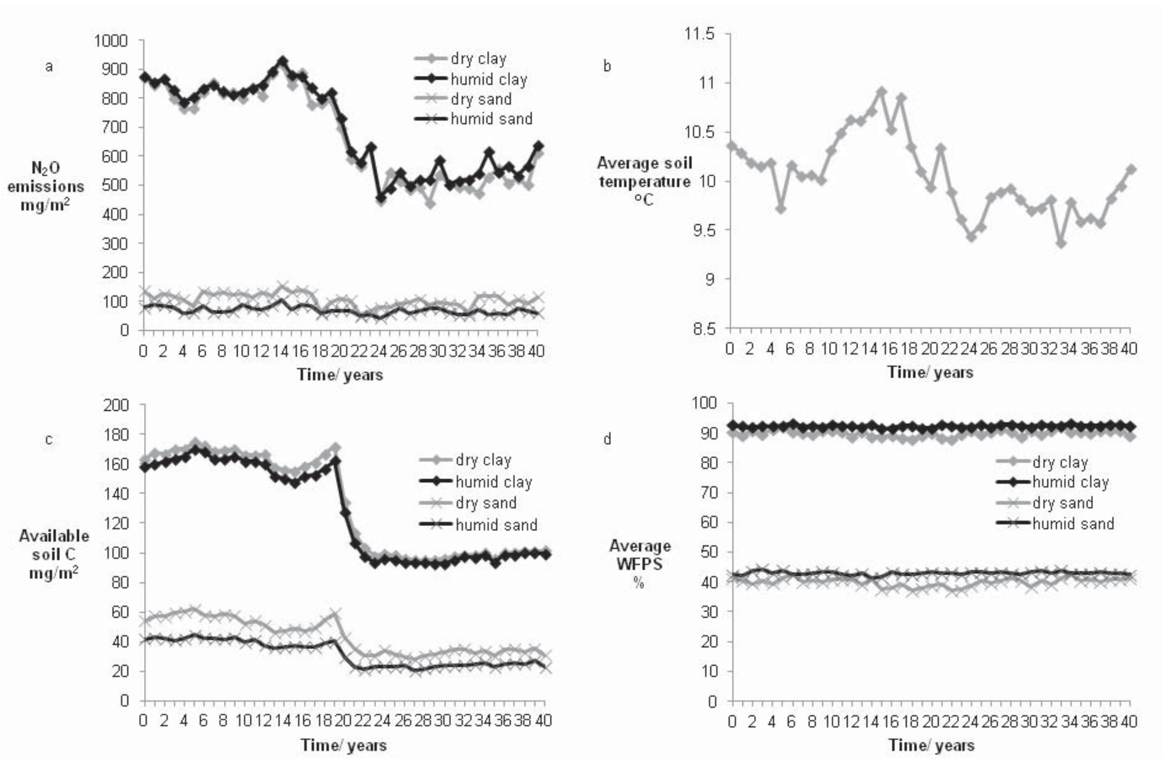

Figure 1: Graphs of DayCent output for (a) N_2O emissions, (b) average soil temperature, (c) available soil carbon and (d) WFPS - before and after cessation of tillage (at year 20)For a,c,d, humid conditions have average annual rainfall of 137cm, 4 times the precipitation of dry conditions, scaled up with the same annual and seasonal distribution patterns.

As shown in Figure 1a, DayCent simulates a decrease in N_2O for NT clay, and no clear pattern for sandy soils. The trend for clay may be partly explained by a reduction in average soil temperature under NT as shown in Figure 1b, as well as the reduction in available soil C shown in Figure 1

c, which more closely parallels the N_2O trend. C and N cycling is represented in coupled pools in DayCent; transfer between N pools is proportional to transfer between C pools, according to C:N ratio, and availability for denitrification or decomposition varies between pools [58]. When DayCent simulates cultivation without tillage, the reduction in decomposition rate results in an increase in C stored as surface residue, and in the slow (i.e. less available) pool. This C pool is coupled to a slow N pool, hence less N is available for denitrification, resulting in reduction in predicted N_2O (and CO_2) emissions. The trend of reduced available C under NT is less significant for sandy soils, due to lower SOM.

Figure 1.d shows no change in WFPS at 20 years, since the model does not represent impacts of tillage on porosity. Soil type appears a more significant control on WFPS than precipitation, which explains the similar N_2O emissions in Figure 1.a for humid and dry simulations. For sand, nitrification is the primary mechanism (as would be expected from low WFPS shown in 1.d) and for clay denitrification is the primary mechanism, which explains slightly lower emissions for dry clay than humid. Further assessment for soils with intermediate drainage indicated a mixture of nitrification and denitrification depending on recent precipitation patterns. Graphs in Figure 1 show annual averages, but it is also useful to look at model performance in terms of short term response to precipitation and nutrient inputs. WFPS at the time of applications of fertiliser controls extent of the denitrification response, which is well represented by the model on examination of data at finer temporal scale in Figure 2. Since impacts of WFPS on emissions are well represented, it is useful to calculate WFPS from an accurate porosity value.

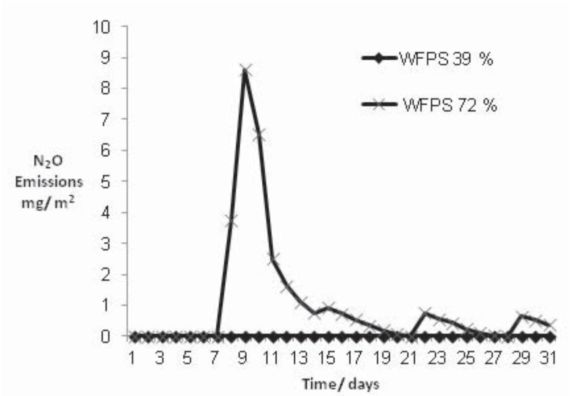

Figure 2: Graph of DayCent output for N_2O emissions from denitrification in response to nutrient application on day 7, for loamy soil at two different WFPS %

Although interaction of nutrients and WFPS is well represented, DayCent fails to appropriately respond to interaction of nutrient applications with tillage. For example, field data indicated greater increase in emissions on addition of fertiliser for tilled soil, compared to untilled soil, whereas DayCent predicted the reverse, for a range of climate and soil conditions [29]. DayCent also gives poor representation of interaction of C:N ratio with tillage regime. In field studies, high C:N had greater emissions for no till, whereas low C:N had greater emissions for conventional till; in contrast, model representation for a range of soil and climate conditions always indicated higher N_2O emissions for low C:N, regardless of tillage regime [61].

Potential changes to the DayCent model

The simplest change is to update SWC for changes in SOM: given the significant correlations identified between these properties, and potentially dramatic variation in SOM over the recommended long set-up period recommended for DayCent This change has potential to greatly improve predictions of SWC, and hence denitrification. Model representation of soil and water processes is outlined in Figure 3.

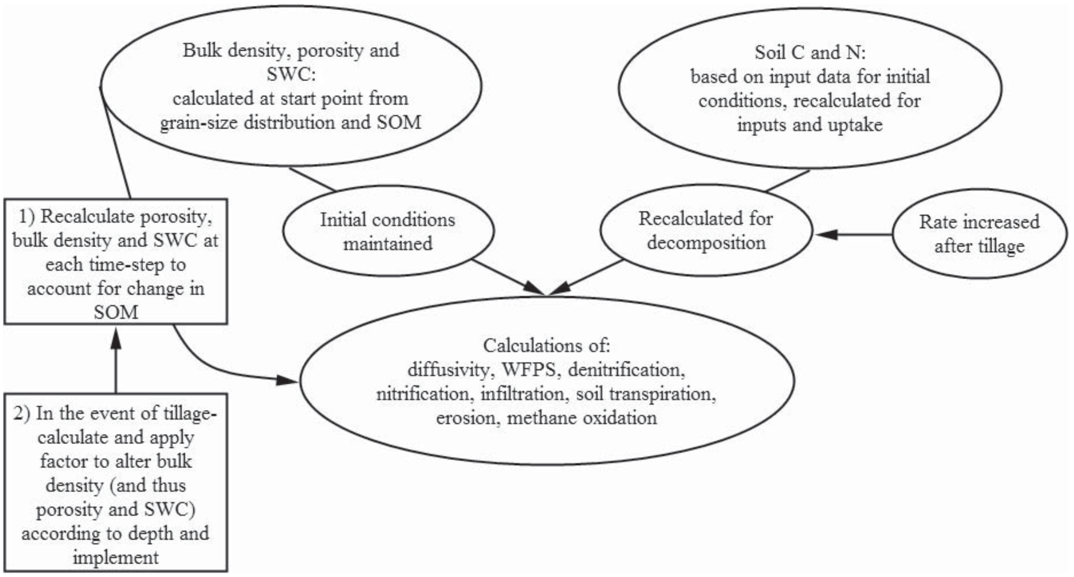

Figure 3: Existing representation of variation in soil properties in DayCent, with potential alterations suggested in square boxes

Figure 3 shows that with the existing representation, C and N are updated at each time step, with impacts of tillage taken into account, but bulk density, porosity and SWC are not recalculated. Since both variable groups are used in the calculations listed, only updating SOM inputs may give inaccurate results. Modifications recommended here aim to rectify this issue. For modification 1, the existing calculation of SWC, porosity and bulk density must be repeated at each timestep. Because the model is made up of separate soil and soil-water sub-models, it is necessary to edit both sub-models, so that agreement is maintained between components.

For modification 2, a factor to represent variation in bulk density (BD) with tillage can be calculated according to:

$$\Delta\rho_{ij} = \mathbf{a + bm_{cl} + cm_{si} + dm_{sa} + eOM}$$

where $\Delta\rho_{ij}$ = change in BD for soil layer and tillage implement
m_{cl} = mass of clay
m_{si} = mass of silt
m_{sa} = mass of sand
OM = mass of organic matter
and a,b,c,d and e are factors varying with tillage implement and soil layer
[62]

Conclusion

Variation in N_2O emissions with conversion to NT is dependent on many interacting site specific variables. DayCent represents variation in soil water, soil C and N, SOM distribution, decomposition (and associated oxygen consumption) over time; however impact of tillage is only represented for decomposition rates. Variation in soil porosity and soil water holding capacity is not represented, and as a single porosity model, homogeneous soil structure is assumed and aggregate stability and macropore connectivity cannot be represented. Hence, DayCent representation of tillage regime impacts on flow is likely to be poor. Recommendations for model development are: updating SWC at each timestep, and applying a “bulk density factor” in the same way as the existing decomposition factor, to enable more accurate calculation of soil oxygen status for N cycling routines. Ideally, basic dual porosity equations would be implemented, and impacts of variation in macropore connectivity and aggregate size and stability would also be represented, but there is a lack of consensus in the literature from which to build equations for macropore and aggregate variation with tillage. Hence, the additional complexity of dual porosity may not be warranted. By representing impacts of tillage regime on more properties, improved scenario analysis should be expected.

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