SIMULATING *NOTHFAGUS* FORESTS IN THE CHILEAN PATAGONIA: A TEST AND ANALYSIS OF TREE GROWTH AND NUTRIENT CYCLING IN SWAT

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Abstract

The SWAT model was applied to the Aysén River Basin of Southern Chile as part of ECOManage, an international project aimed at make available modeling and decision-making tools for managers of coastal zones. This heterogeneous basin of 11,456 km^2 presents a modeling challenge due to the mountainous terrain, strong precipitation gradient and the importance of non-agricultural land cover types. The low nitrogen deposition and cold climate of Chilean Patagonia place restrictions on the nitrogen cycle in the forests of the region. After presenting the results of the hydrodynamic calibration of SWAT for the Aysén Basin, we analyze the importance of vegetation growth and litter production in the nitrogen cycle of evergreen and deciduous *Nothofagus* (Southern Beech) forests. We compare SWAT2000 and SWAT2005 in terms of tree growth and the nitrogen cycle. Finally, we present our conclusions as to the most appropriate way to simulate *Nothofagus* forests while trying to balance model complexity and data requirements with the realism of the simulations.

KEYWORDS: SWAT, nitrogen cycle, forest growth, Patagonia

Introduction

The application of complex watershed simulation models to basins that are quite distinct from those used for model development can lead to unexpected difficulties. One potential pitfall is the issue of equifinality where numerous parameter sets can lead to statistically acceptable results. However, unless one delves into the details, examining the behavior of different modeled processes in different land use/soil combinations, using the model as a predictive tool is not recommended. In this paper, we examine in detail nutrient cycling and plant growth in a remote basin in the Chilean Patagonia. This basin presents a case study that is highly divergent from the low-topography agricultural basins originally used as references for the creation of SWAT and related models. Additionally, ecological research in the past two decades has uncovered several singularities in the nutrient cycling of Patagonian forests. This paper addresses the challenges and solutions involved in applying the SWAT model in the Aysén Basin.

The SWAT model was used in European project EcoManage as a tool to increase the capacity of assisting managers of Coastal Zones to join knowledge horizontally from ecological and socio-economic disciplines. The Aysén Fjord is an interesting study site because it shows conflicting interests between urban, industrial and agricultural pressures and environmental maintenance. The three key aspects of EcoManage are (1) the consideration that a coastal zone depends on local pressures, but also on pressures originated in the drainage basin, transported mostly by rivers and by groundwater, (2) that socio-economic activities are the driving forces of those pressures and that their impacts on the Coastal ecosystem have feedback on socio-economics and (3) the impacts depend on physical characteristics of the Coastal ecosystem that together with the loads determine its ecological state.

Review: Nitrogen Cycling in Southern Chile

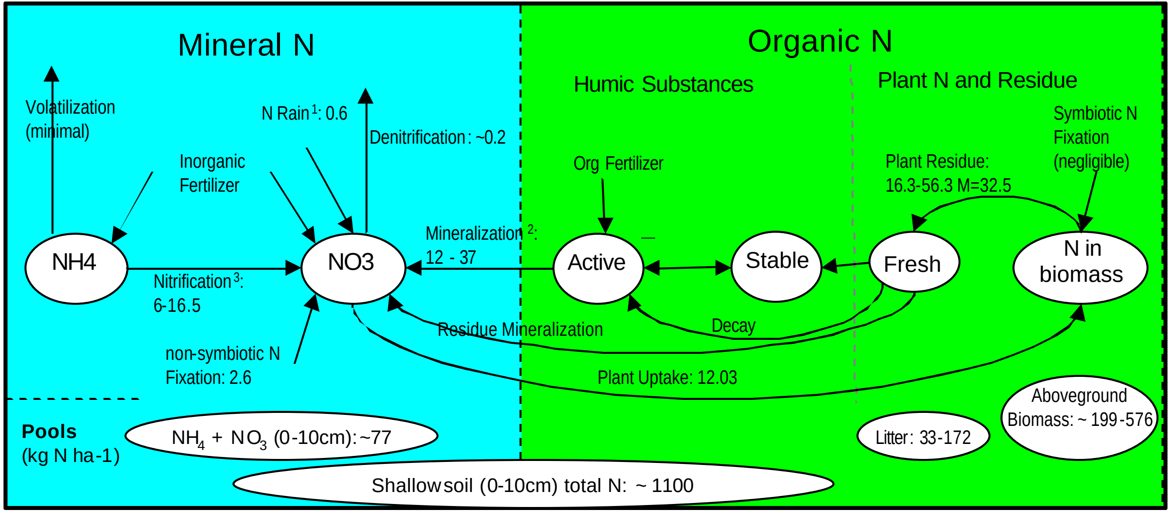
Nitrogen and phosphorus are thought to be the key elements in limiting primary productivity in temperate forests (Attiwell & Adams 1993). Thus, it is important to gain an understanding of these cycles in any particular forest type or geographic location. The Aysén Basin is located at about 45° S in the XI region of Chile. However, the bulk of what is known about nutrient dynamics in Patagonian forests comes from other geographical areas such as Chiloé Island, (approximately 300km northeast) of the Aysén basin and Puyehue National Park (500km to the north).

Perhaps the most outstanding feature of the Southern Patagonian forests is their isolation. In a biogeographical sense, this isolation has led to high rates of endemism as well as restricted biodiversity. Currently, a major effect of isolation is that rates of wet and dry nutrient deposition remain similar to historic rates, while in the northern hemisphere these rates have been severely altered (Godoy et al. 2003; Oyarzún et al. 2004). As a first approximation, forests in the Chilean Patagonia would be expected to have high internal nutrient cycling resulting in low nutrient loading to rivers. However, the creation of pastures by burning and the subsequent introduction of cattle and sheep into many areas (especially valleys) of Patagonia have altered watershed dynamics in ways that are not yet fully understood.

Several processes and pools of the nitrogen cycle of the Patagonian forests have been studied a good deal, while for others, published information is scarce (see Figure 1). Several authors have commented on the limited inorganic N wet deposition to forested ecosystems in Southern Chile, where concentrations range from 0.015 to 0.071 mg/L (Hedin et al. 1995; Perez et al. 1998; Godoy et al. 2003). However, organic N in rainwater and especially cloudwater from biogenic and anthropogenic sources can contribute significantly to the total N deposition (Godoy et al. 2003). This appears especially true in coastal areas, where cloudwater can deliver up to 9 kg ha-1 yr-1 of organic N (Godoy et al. 2003). Net N mineralization has also been studied in Patagonia and reported values of between 12 to 37 kg N ha-1 yr-1 have been reported, significantly less than forested systems with anthropogenic N inputs (Pérez et al. 1998; Pérez et al. 2003a). Nitrification was demonstrated to be between 50% and 62% of total N mineralization for forests in Chiloe (Pérez et al. 1998). SWAT directly calculates mineralization of organic N fractions to nitrate, therefore including a nitrification step. Ammonium in the terrestrial SWAT2000 N cycle only derives from fertilizer (including animal grazing), and thus NH_4 loading to rivers and volatilization will be zero unless fertilizers are used or water quality processes are activated. This contrasts with data from Patagonia which indicate that the average ratio of nitrate: ammonium is low in (a) rainwater (0.2 in Puyehue Park), (b) in soil water (ca 0.44 for shallow water and 0.03 for deep water) and (c) runoff (consistently below 1 and often below 0.1) (Perakis & Hedin 2002; Oyarzún et al. 2004, Perakis & Hedin 2005). Because these basins are largely forested, they have little to no fertilizer input and thus in SWAT there is no NH_4 in the terrestrial N cycle. In SWAT 2005, a new natural source of N was included: NH_4 in rain.

Denitrification can be generally characterized as low in well-drained forested soils and higher in wetter floodplain areas. Pérez and colleagues (2003a) show that denitrification in temperate forests of Chiloe Island are low: roughly 0.2 kg ha-1 yr-1. Although, measured data are not available for the Aysén Basin, it is hypothesized that denitrification maybe higher in the western fringe where precipitation can surpass 4m yr-1, or in specific patches of wetland soils in the flatter and drier eastern fringe. While the *Nothofagus* genus, the dominant trees in the Aysén, does not have symbiotic N-fixation, non-symbiotic N-fixation takes place in the woody debris and litter on the forest floor. Pérez and colleagues (2003a) report that non-symbiotic fixation in Chiloe ranges between 1.5-3.6 kg N ha-1 yr-1. Volatilization of nitrogen does not appear to be important in the nutrient cycle of Patagonian forests, according to an N tracer study by Perakis and Hedin (2001).

To synthesize the above: tight N cycles have been documented in several Patagonian temperate forests and would be expected in areas not yet intensively studied. Wet deposition of N is generally very low, especially for inorganic fractions (Godoy et al. 2003). Mineralization and nitrification were consistently lower than most forest from the Northern Hemisphere (Pérez et al. 1998). Inorganic N appears to be rapidly taken up by microbes and vegetation, and soil and stream measures of nitrate are often very low (Perakis & Hedin 2001; Perakis & Hedin 2005). Dissolved organic nitrogen makes up the bulk of exported N in forested watersheds and appears to be controlled by hydrological factors instead of by microbial processes or plant uptake (Perakis & Hedin 2001). Because of scare available N, turnover rates of canopy foliage tend to be low: on the order of 5 years for broad leaf evergreen forests and 15 years for conifer-dominated forests (Pérez et al. 2003b).



[1] This is a value for NO3, total N contribution via precipitation can reach 11.8 kg ha-1 yr-1

[2] net mineralization in 0-10cm of soil, (includes organic to NH4)

[3] nitrification estimated as 50% of net mineralization (Perez et al. 1998)

Figure 1: Diagram of N cycle in SWAT2005 with pools and process rates for Patagonian forests taken from the literature. (Diagram adapted from SWAT2005 Theory)

Potential Problems Modeling Patagonian Forests with SWAT

The SWAT model is now widely applied around the world; however, it has been most frequently tested using data from low topography agricultural watershed in the American Midwest. Users applying the model to unique basins should proceed with caution in order to make sure modeled processes in SWAT fit with what is known about a particular basin. Because the Aysén basin is heterogeneous basin with a predominance of non-agricultural land cover types we examine potential problems that may arise in modeling plant growth and nutrients with SWAT.

Tree growth and organic residue

SWAT inherited plant growth algorithms from the EPIC model, which were created for use in highly agricultural settings (Gassmann et al. 2005). Fundamental differences in agricultural and forest systems and the fact that SWAT does not explicitly model the carbon cycle have lead several researchers to incorporate more realistic forest algorithms into SWAT (Watson et al. 2005; McDonald et al. 2005). This work is certainly valuable; however, due to lack of data in many parts of the world, adding more complexity to SWAT may not necessarily improve results. We attempt to improve nutrient cycling in SWAT by fine-tuning existing algorithms and without incorporating a full accounting of the carbon cycle.

Because exogenous nutrient inputs into forests systems in southern Chile are minimal, litterfall is an important source of bioavailable P and N. It is thus important to examine the residue production in each landuse type and to verify the fate of this residue.

Too much N in wet deposition

The default value of the RCN parameter (nitrate in precipitation) in SWAT is 1 mg/L. However, Oyarzún and colleagues (2004) indicate that in the Andes range of the X region of Chile the concentration of total N in precipitation is 0.174 mg/L. Furthermore, unlike the northern hemisphere where the majority of wet deposition N is inorganic, in southern Chile most deposition occurs as dissolved organic nitrogen; Oyarzún et al. (2004) found 66% of N in precipitation was organic N. Other authors have found similar patters (Godoy et al. 2003). Thus, it would be more realistic and likely to provide better results if the N in precipitation could be divided into its major fractions and introduced directly into the appropriate pools.

The objective of this work was to address the following problems and concerns in the context of the Aysén basin. A final objective is to produce a SWAT output file that expedites the visualization and analysis of nutrient cycles for the entire basin and for different types of HRU.

Calibration and Validation of SWAT for the Aysén Basin

Data and Model Setup

The SWAT model was set up in AVSWAT-X and pre-existing data for the region was used. A descriptive study of the regions soils by IREN-CORFO (1979) was augmented by data provided to ECOManage by SAG (Agriculture and Livestock Service) in 2006. Pedotransfer functions which allow the estimation of hydraulic soil properties like porosity, field capacity, wilting point and conductivity were used (Saxton et al., 1986). The official land register of native forests (CONAF-CONAMA 1997) was used to characterize the current landuse. Because the database includes a large number of land cover classes, the information had to be converted (and simplified) into a format usable by SWAT. Additionally, because of the dominance and diversity of forest cover in the basin, new SWAT classes were created based on an extensive literature review and expert opinion (Table 1). Meteorologic and streamflow data were obtained from the General Water Authority (DGA). Due to the extreme spatial heterogeneity of precipitation in the Aysén Basin, the simple algorithm used by AVSWAT-X to assign precipitation stations to subbasins was not adequate. First, 'synthetic' were added: multiplying an observed precipitation station by a constant factor in order to bring the annual average precipitation in line with the isohyets generated by the DGA. Second, precipitation stations were manually assigned to subbasins in order to approximate the isohyets.

Table 1: New SWAT Land Cover Classes Used in Aysén SWAT Model

SWAT Code	Vegetation Type	Principal Species	Range of litterfall (Mg ha-1 yr-1)	Simulated residue, range and mean (Mg ha-1 yr-1)
BCAY	Deciduous forest of Aysén	*Nothfagus pumilio*	2.0 - 3.6	1.9 - 4.2; 2.93
MCAM	Montane deciduous forest	*N. Antarctica, N. pumilio, Berberis spp.*	1.4 - 2.5	1.2 – 2.8; 1.94
BSNB	Montane evergreen forest	*Nothfagus Betuloides, Laurelia philippiana*	2.8 - 3.8	2.3 – 3.82; 3.19

Sources: Caldentey et al. 2001; Austin & Osvaldo 2002; Vann et al. 2002; Pérez et al. 2003b

Model Calibration and Validation

A sensitivity analysis was run for the model setup and autocalibration was carried out using the ten most sensitive parameters. Only the basin output point (Aysén River monitoring station) was used for autocalibration; however, limited manual calibration was carried out in specific subbasins. SWAT hydrodynamic calibration results can be seen in Table 2.

Table 2. Comparison of observed and modeled average monthly flows and daily and monthly R2 and model efficiency statistics

	Station	Time period	Observed / modeled flow (m^3/s)	R2 Day/Month	ME Day/Month
Calibration	Aysén	Jan '96–May '98	556/582	0.54/0.86	0.5/0.73
	Mañihuales	Jan '96–May '98	187/173	0.53/0.75	0.51/0.73
	Simpson	Jan '96–May '98	47/62	0.67/0.83	0.55/0.59
Validation	Aysén	Sep '02-Sep '05	599/507	0.48/0.67	0.33/0.41
	Mañihuales	Jul '02-Jul '05	201/167	0.52/0.79	0.5/0.7
	Simpson	Feb '02-May'05	60/43	0.56/0.61	0.42/0.41

Modeling the Nutrient Cycles of *Nothofagus*-dominated watersheds

Tree growth and residue production

SWAT outputs the biomass generated in each HRU, and though for agricultural landuses this figure may be directly compared to crop growth and harvest, the situation for forests is more complex. In SWAT2000, interannual tree growth did not occur: all forest HRUs were considered to be mature. In SWAT2005, tree growth from sampling to mature tree is able to occur (Figure 2). However, under default tree parameter sets (e.g. PINE) a large fraction of annual biomass production is removed as yield or converted to residue, resulting in minimal growth of persistent biomass such as trunks and large roots. If the primary objective for calibrating biomass is to achieve realistic nutrient cycling, then the total biomass of a forest system can be ignored and the focus can be placed on residue production. This is our strategy. In Table 1, the ranges of litterfall for the three principal forest types in the Aysén basin were gathered from the literature and compared to SWAT output after calibration. The most sensitive parameter modified was BIO_LEAF which controls the fraction of biomass converted to residue at the end of each season. Other parameters changed—according to values found in the literature—were the nitrogen and phosphorus uptake parameters, LAI, canopy height, rooting depth, and the harvest index.

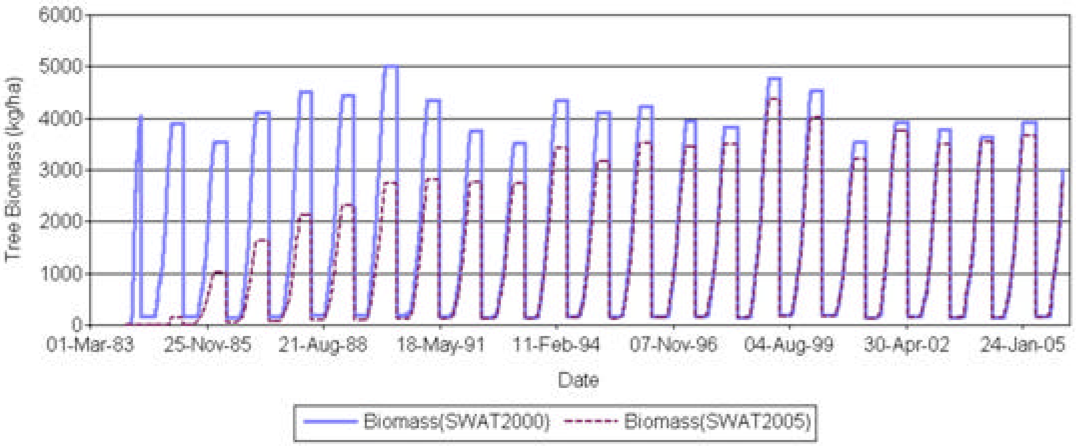


Figure 2. Difference in biomass production between SWAT2000 and SWAT2005 for Nothofagus pumilio.

Modification of wet deposition

An option in SWAT2005 is to split wet deposition of N into NH_4 and NO_3 components. However, the literature from Patagonia indicates that dissolved organic nitrogen (DON) can make up one third of wet deposition (Oyarzún et al. 2004). Thus, source code was changed to allow DON to be added as a component of wet N deposition.

After a spin-up period of 6 years, we compared the average daily NO_3 concentration at the subbasin that corresponds to the Aysén River monitoring station with 28 measurements of NO_3-N taken between 1997 and 2004 by the local authorities. The average measured value was 0.048 mg/l while SWAT NO_3 output for the corresponding reach was 0.053 mg/l. The difference between modeled and measured values was not statistically significant (t= 0.91, p=0.37, gl=27). The same simulation set up, run with RCN = 1 gives a NO_3 concentration in the reach of 0.23 mg/L, which is higher than even the highest measured value. Table 3 indicates that reducing NO_3 in rain (to levels measured in Patagonia), adding DON as input, and adjusting related parameters can produce good results.

Table 3. Estimated annual nitrogen and phosphorus loads from diffuse sources.

Simulation Run	N (tons/year)	P (tons/year)	% Org N
RCN = 1	7674	436	29%
RCN=1, N parameter set	4592	231	24%
NH4=0.049, NO3=0.01, DON=0.115, N parameter set	2776	288	56%

(N parameter set: RSDCO = 0.005, SDNCO = 0.95, NPERCO = 0.005)

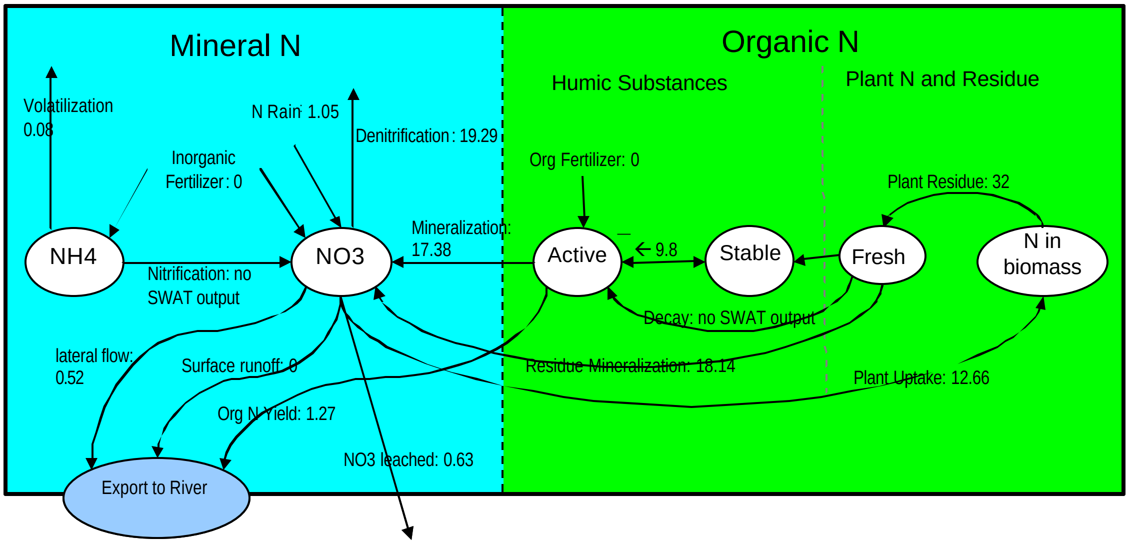


Figure 3. Output of SWAT2005 after calibration and changes for BCAY forest type (kg N ha-1 yr-1)

A more detailed look at the model results after changes in the N cycle parameterization and wet deposition can be seen in Figure 3. In general, the values of the annual processes in the N cycle are within the range of literature values given in Figure 1. One process where the model and field data do not match is denitrification. This might partially explained by the fact that SDNCO (denitrification threshold water content), has been adjusted down slightly and that CDN (denitrification exponential rate coefficient) was left at its default value. It is likely that further adjustment to existing parameters can help decrease the model value; nevertheless, it is also important to consider if the little published denitrification data (which is hard to measure reliably in the field and often is variable in time) are too low. In Aysén, the high rainfall and high organic soil matter should allow for more denitrification. Another point is that the active organic to stable organic N value is negative, and more generally, net mineralization occurs consistently during the simulation period. This might act to drive more denitrification than would otherwise occur. A qualitative indicator that the current SWAT setup is appropriate for Patagonian forests is that the ratio of external:internal N cycle fluxes is 0.4. This fits with statements by Pérez and colleagues (2003a) that the N cycle in Patagonian forests tends to be tight with much internal cycling.

Conclusion

In this paper we have taken steps to improve the ability to model watersheds dominated by relatively unpolluted temperate forests with SWAT2005. Our strategy has been to make small modification instead of adding more complex routines requiring additional parameterization or input data. We have seen results improve: the ratio of organic N to inorganic N in river water has decreased as we have calibrated and then modified the model. Apart from a few processes, the annual fluxes in the SWAT N cycle for the BCAY cover class corresponded to what were gleaned from the literature. As more data becomes available on the soils, forest dynamics, and nutrient cycles for the Patagonian region, it will be desirable to increase the complexity of the model for those routines where results are sub par. This work has already begun (e.g. Watson et al. 2005; McDonald et al. 2005). However, with the limited data currently available, we conclude that SWAT2005 is capable of simulating the N cycle in a unique forested system.

We used a SWAT2005 version in which the source code was partially modified—the inputs and outputs of the model—using MOHID's code and programming philosophy (Chambel-Leitão et al. 2007). This has improved analysis and visualization of admittedly complicated N cycles in large basins. Furthermore, a macro created in Excel allows diagrams such as the ones in this paper to be rapidly produced. Further work is continuing on adjusting the N cycle and P cycles in SWAT for Patagonian forests. One expected outcome is to be able to identify the most pressing gaps in field data. A final outcome for the ECOManage Project will be to produce a working set of tools and models for managers and policy makers for the Aysén Basin.

In concluding, we wish to mention the utility of using SWAT with the three wet deposition compartments (NH_4, NO_3, and DON) as a way to study the potential effects of increasing anthropogenic N emissions worldwide and the interactions between climate change and biogeochemical cycles.

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