Modelling Nitrate Formation and Movement in Vineyard Soils – A Contribution to a More Sustainable Viticulture

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Abstract. Ecologically sound production is a catchword used in nearly all viticulture production areas. Besides the pesticides inputs which are unavoidable specific attention is directed to nitrates which can pollute ground water reserves and may have some adverse effects to humans after consumption. There are two main sources for nitrate in vineyard soils: a) mineralization of humic compounds from the soil and b) nitrogen fertilization. In the latter case the inputs can be controlled via balance sheets, which are obligatory in Germany for instance. During a six years period the mineralization process of slowly decomposable organic matter in vineyard soils was evaluated.

As a basis STANFORDs equations were used to describe that process but could finally reduced to a zero order equation. These findings were combined with different sub-models from soil science: heat transfer and water movement. Input values are very simple to determine: global irradiation, soil texture (sand, silt, clay) and wet digested organic matter (WALKLEY-BLACK). The compiled model is deterministic. Therefore it is transferable to other, unknown sites. The nitrate dynamic in soils can be followed up with one starting value which under German conditions is determined after harvest or in early springtime: the calculation includes the soils water content, the nitrate concentrations, possibly nitrate losses, and the NO$_3$-content at the point of planned fertilization.

Normally the mineral fertilizer input can be reduced without endangering yield and quality of grapevines. The model is now used as a tool for the extension service. On the other hand it is a powerful proof that viticulture, which is mostly carried out in vulnerable land sites, can save the environment for future generations.

Keywords: viticulture, nitrate, mineralization, modelling, fertilization.

INTRODUCTION

Ecologically sound production is a catchword used in nearly all viticulture production areas. The first idea about that topic may probably deal with the application of pesticides because their impact on biocenosis is obvious. On the other hand side nutrients, which are necessary for optimal yields and quality may affect surface and ground waters after erosion or leaching.

One of the main pollutants is nitrate, which is highly soluble, as an anion not fixed on the soil exchange complex and harmful to humans after ingestion.

Two main sources for nitrates in soils are known:
- a) mineralization of nitrogenous humic compounds
- b) application of nitrogen containing mineral fertilizers

The application of nitrogen fertilizers is a well known technique: the inputs are normally calculated from plant uptake and removal. Therefore possible risks from overfertilization can be minimized, especially when the nutrients are applied in accordance with the plants uptake rhythm (Löhnertz and Schaller, 1992).

A real gap exists concerning the contribution of soil organic matter to the nitrate fluxes in soils. A lot of publications are available which deal with the potential nitrogen output of
different organic materials, which can be applied to soils as restoration material for organic matter losses. That figures are more or less general and give only an information about the total amount but there is no idea about time dependant fluxes.

Whilst vineyards are located in specific landscapes (steep slopes and river benches), it is important to know the internal nitrate build up in the soils and possible contributions of environmentally harmful nitrates to ground and surface water; on the other hand additional inputs with mineral fertilizers can be reduced.

**MATERIALS AND METHODS**

During a six years experiment different vineyard sites in the Rheingau region were examined for their mineralization capabilities. The sites represented the main soil groups, which can be there found. Prevailing types are loess, sandy loess and clayey soils.

In all soils a textural analysis was made, and soil C and N was determined following a modified procedure of WALKLEY and BLACK (Sims and Haby, 1971). In addition soil physical parameters were estimated in undisturbed samples: water retention curve and hydraulic conductivity.

The mineralization of organic matter was performed on undisturbed soil samples and disturbed ones (Cabrera and Kissel, 1988).

In the first case 250 mL stainless steel cylinders were used to extract samples from 0-5, 15-20, 20-30 and 50-60 cm depth. In the latter case, soil from the corresponding depths was crushed in a wet mill, diluted 1:1 with quartz sand, filled back in stainless steel cylinders and re-compacted in a Proctor apparatus to the same density as the undisturbed samples. After that, samples were wetted with distilled water to pH 1.8 and incubated in an oven with controlled temperatures at 5, 15, and 35°C. Every fortnight triplicate samples were analysed for nitrate and ammonia. The total observation time was 190 days.

**Calculation of the potential mineralizable nitrogen (N_{pot}) and the mineralization constant (k).**

From the calculated gradients of the mineralizable N against time a first estimated value for N_{pot} is found (Stanford, 1972). From N_{pot} and k the potential mineralizable N can be calculated per time unit.

\[ N_t = N_{pot} \times (1 - e^{-kt}) \]

**Alternative Calculation**

1. Estimation of N_{pot} directly from the incubation experiments with a regression equation
2. With the N_{pot} value for every single measurement k value is calculated and finally the arithmetic means is formed.

**Agro-meteorological measurements**

Radiation balance and albedo in 2 m height; soil surface temperature and soil temperature in 2, 5, 10, 20 and 50 cm depth. These data were continuously logged and transformed to hourly mean values. Rainfall and evaporation were used from the observation plots of the German weather service

**Models**

The leaching of nitrates in a distinct soil profile is dependant from the processes which run the zone of soil moisture as well as from amount of N-uptake by the growing plants. These processes are in an active interaction with the hydrological and thermal sub processes.
Basically all macroscopic processes can be drawn back to transport and transformation processes. Transport is a vectorial unit and is driven by a gradient. Velocity is determined by the amount of the gradient and that of the transport parameter. However, transformation processes are to be observed as scalar.

A series of model equations was developed for nitrate movement, N-mineralization, soil heat transfer, water transport, soil water budget, soil heat budget, and soil unsaturated hydraulic conductivity. Detailed description can be found in Schaller et al. (1994).

Input parameters for the model are: soil saturated hydraulic conductivity, soil heat conductivity, soil density, soil specific heat, pF characteristic, pore volume, diffusion coefficient. Start values for volume water content (\(\phi\)), temperature (t) and nitrate content (NO\(_3\)). Additional values: daily global irradiation, daily rainfall and wind velocity, daily mean as well as minimum and maximum of air temperature. Mineralization coefficient and N\(_{\text{pot}}\). Most of these values have to be determined for a plot only once, i.e. as soil characteristics and the others are available through the weather services. A model was compiled named NITBIL, which allows the calculation of nitrate build up, movement, possible losses and start values for fertilization.

RESULTS AND DISCUSSION

**Evaluation of mineralization constants**

As described above mineralization is strongly dependant from the mineralization constant, which itself is mainly driven by temperature and to a lesser extend by soil moisture, supposed soil moisture is in the range from pF 1.8 to 2.5-3.0 (Fig. 1).

![Fig. 1](https://example.com/fig1.png)

It is remarkable that at different soil depths the k values differ significantly, i.e. if a correct estimation of the nitrate formation in a soil is expected, it is not possible to work only with one k-value for all soil layers; in contrary a correct determination has to be done in order
to make the right computations. It is also necessary to work out the influence of different tillage systems. We can demonstrate that the introduction of a permanent grass cover will alter also the k-values (Schaller et al. 1994).

The calculation of the k-values was at first proposed by Stanford (1972). During our experiments it was found out that there is a possibility to calculate k values with regression equations. The assumption that the Stanford procedure is more reliable than the regression systems could not be verified. In contrary model calculations with different soils revealed that there is nearly no difference between both systems (Schaller et al. 1994).

The k-values worked out for the different soil types are not uniform and differ between the examined soil types. There not only a differentiation between soil depths and types but also between soil management systems. Stanford (1972) proposed a “universal” k-value, which is valid for all circumstances. That hypothesis could not be verified during our work.

**Relations between soil organic matter and N mineralization**

During the series of incubation experiments in every sample organic C and N was determined following the modified procedure of Walkley and Black (Sims and Haby, 1971). A clear relationship between oxidizable C and mineralised N could be established (Fig. 2). A curvilinear relationship exist for all tested soils between organic matter content and released N. A strong dependency between soil temperature and mineralised N is also obvious.

<table>
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<th>Temperature (°C)</th>
<th>ax²</th>
<th>bx</th>
<th>c</th>
<th>r²</th>
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<tr>
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</table>

It seems that with that relationships the process of N release can be described very well. From 10°C upward to 35°C the coefficient of determination is quite high and significant. In the range of 5°C, which is common during wintertime, the nitrates formed during that period and temperature regime do not exceed 5-10 kg N/ha. Comparisons showed that the amount of nitrate, which mineralised at 5°C reaches only 1% of that formed at 35°C. Also additional introduced parameters like clay content or the ratio of organic C to clay content improved the relation only slightly. For further investigations it is important to know that the fraction of “easily” oxidizable soil organic C has utmost significance for soils’ N release. This parameter is easy to determine and together with the other variables needed (see methods) the model can be build up with relatively simple available variables.

**Comparison Stanford k and alternative k**

Normally it can be found in the literature that most of the research groups dealing N-mineralization accept the k-values proposed by Stanford. However, we found out that the k-values will vary with soil type, depth and type of organic matter (Schaller et al. 1994). Implementing such a universal value in a model can cause problems especially when the model has to be validated. During that process it is possible to “correct” the specific value. If this is the correct way of model building is another question.
Two runs were made with a typical soil from the Rheingau area comparing the calculated values with the measured ones. The calculation was done with the real site values, i.e. in situ soil temperatures, rainfall, and soil physical parameters (Fig. 2).

Fig. 2 Nitrate formation in vineyard soil in four different soil layers (0-80 cm) (Geisenheimer Mäuerchen) calculated with help of two mineralization coefficient.

Left: Stanford “universal” k. Right: own values. Worked out after incubation and regression analysis.

Without any difficulty it can be seen that with the Stanford k nitrate formation in the soil is tremendously overestimated. That happens especially in the upper soil layers. With exception of the starting point(s) there is no correspondence between calculated and measured values.

The run shown on the right side of figure 2 demonstrates that the model implemented with the alternative k values reflects a very good accordance between calculated and measured nitrate values. Projected on a hectare basis the differences range from 7 to 20 kg N/ha. Keeping in mind that the soil testing procedure has also a higher variability, nearly no distinction can be made between both measures. In another compilation for a fertile soil the “true” Stanford k and our alternative k values were used in order to calculate the mineralised N for a one year period. It could be demonstrated that in the first case >400 kg N/ha were estimated and in the latter 120 kg N/ha, that corresponds to a mineralization rate of 2.8-3.0% versus 1.2-1.5% (Schaller et al. 1994).

Final model

As described above, a model was compiled with some well known algorithms for water movement, heat transfer together with the mineralization module which comprises the
new k-values for different soil tillage systems and the specific temperature influences on the n-mineralization.

The model NITBIL allows to calculate with one starting point for soil $N_{\text{min}}$ content, which is normally determined during autumn or late winter, to estimate the complete mineralization, the leaching of nitrates and finally the residual nitrate in the soil profile (0-90 cm).

The latter value is important for viticulture because it is used to calculate the starter N fertilization in springtime. It is assumed that the nitrates in the profile are available for the grapevine and as a consequence it is subtracted from the planned mineral fertilizer application.

A complete run for the period winter – end of May is shown in Fig. 3.

![Fig. 3. NITBIL calculation for the site “Geisenheimer Mäuerchen” for the period end of November – end of May. * indicates soil nitrate tests.](image_url)

It can be seen that the differences between calculated and measured soil nitrate content in springtime is very small.

**CONCLUSIONS**

The results of our investigations indicate that nitrate formation is a central process in soils and that the knowledge of it is important for an ecologically sound and sustainable viticulture.

Nitrogen is an essential element which is needed by the grapevine in distinct amount during the growing season. The uptake rhythm shows two peaks after bloom and shortly after veraison (Löhmertz, 1988). In every case, parts of the released N out of the organic matter can also be used by the grapevines. Therefore the application of mineral fertilizer has the role of a sustaining action, i.e. increasing the nitrate content in the soil solution in order to foster the uptake and ensure a sound plant growth.

The findings of that work culminated in a model called NITBIL, which allows to calculate the nitrate formation in vineyard soils including some additional information like...
leaching, total mineralization and plant available water. This is of important value for extension services who can use this supplementary information for extensive advices.

Currently the program is not so comfortable that it can be used on every desktop PC because the surface needs to be more user-friendly. However, if a user is experienced it is a very useful tool. In Germany NITBIL is currently used by the German Weather Service (DWD) in order to prepare at the begin of the growing period a weather fax with information about the soil nutrient status and hints for nitrogen fertilization of the grapevines.

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REFERENCES