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Nitrate Contamination of Groundwater in Austria: Determinants and Indicators

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Abstract

Nitrogen is an important input to agricultural production but also detrimentally affects the environmental quality of air, soil and water. Identifying the determinants of nitrate pollution and in turn defining sensible performance indicators to design, enforce and monitor regulatory policies is therefore of utmost importance. Using data on more than 1000 Austrian municipalities, we provide a detailed econometric analysis of (1) the determinants of nitrate concentration in groundwater, and (2) the predictive abilities of one of the most commonly used agri-environmental indicators, the Nitrogen Balance.

We find that the proportion of cropland exerts a positive effect on the nitrate content in groundwater. Additionally, environmental factors such as temperature and precipitation are found to be important. Higher average temperature leads to lower nitrate pollution of groundwater possibly due to increased evapotranspiration. Equally, higher average precipitation dilutes nitrate content in the soil, reducing nitrate concentration in groundwater.

To assess the Nitrogen Balance, we link observed pollution levels to the theoretical indicator and evaluate its ability to measure nitrate pollution effects. Indeed, the indicator proves to be a good predictor for nitrate pollution. We also show that its predictive power can be improved if average precipitation of a region is taken into account. If average precipitation is higher, the Nitrogen Balance predicts nitrate levels in groundwater more precisely.

Keywords:
nitrate concentration, groundwater, Nitrogen Balance, agriculture, regression analysis.

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1. Introduction

Nitrogen is one of the major nutrients applied in agriculture to increase crop production. However, excess supply of nitrate can lead to environmental damage, causing contamination of the air, soil as well as water. In particular, since reactive nitrate is highly soluble, excess easily leaches into groundwater aquifers, where it contaminates drinking water. In the present article, we focus on the effect of agricultural nutrient losses on groundwater quality, as this poses immediate risks to human health, and is thus arguably one of the most prevalent impacts of nitrate overuse in agriculture (Schroeder et al. (2004), Lord and Anthony (2002)). Excessive nitrate intake may cause methemoglobinemia in infants (i.e. a decreased ability of the blood to carry oxygen) and is sometimes associated with an increased risk of certain cancers in adults (Fan and Steinberg (1996), Weyer et al. (2001)). The World Health Organization as well as the European Union recognize this threat by setting the acceptable threshold of nitrate concentration in groundwater to 50 mg/l (European Council (1991)).

In order to choose appropriate policy measures to regulate excessive nitrate use, the economic theory of external effects highlights the necessity to "set incentives right". Nitrate (over)users have to take into account the external effects of their activities, so that a social optimum is reachable (Oenema et al. (1998)).

In this vein, two obvious questions arise: (1) What should be regulated? To answer this question, we identify the more (and less) important determinants of nitrate contamination of groundwater. (2) On what grounds should be regulated? In particular, which indicator can be used to design and evaluate policies concerning nitrate use? The most commonly used measure to guide policy interventions to date is the so-called Nitrate Balance. We discuss whether this indicator is indeed a good proxy for observed environmental pollution and thus whether its frequent use in guiding policy is justified. In addition, we assess if and how this particular indicator can be improved.

Choosing appropriate policy measures to tackle the problem of nitrate contamination is challenging, since the determinants of nitrate pollution of groundwater are not obvious (Sieling and Kage (2006), de Ruijter et al. (2007), D'Haene et al. (2003), Elmi et al. (2002)). We fill this gap in the literature by providing the (to our knowledge) first systematic, full-fledged econometric analysis of the determinants of nitrate contamination of groundwater. To this end, we constructed an extensive and very detailed data set on the Austrian situation. We are able to point out which agricultural practices are prone to pollute the quality of groundwater as well as highlight the role of certain external factors such as weather conditions (Boumans et al. (2001), Fraters et al. (1998)) or soil characteristics (D'Haene et al. (2003), de Ruijter et al. (2007)), suggesting that these should also be taken into account when designing policy measures (Sieling and Kage (2006)). Our econometric approach offers several improvements upon work based on experimental data (Buczko et al. (2010)). Within our setup, we are able to identify the marginal effect of several potential explanatory variables separately and, since we perform our analysis on a very large and detailed data set, we offer a tool to forecast potential nitrate pollution of groundwater given agricultural practices as well as weather and soil conditions.

To formulate policy objectives, monitor policy compliance as well as its effectiveness a meaningful criterion is needed (de Ruijter et al. (2007), Watson and Atkinson (1999), Lord and Anthony (2002)). As mentioned, the currently most commonly used indicator to monitor and assess nitrogen use across countries is the so called Nitrogen Balance[1] (Parris (1998), van Eerdt and Fong (1998), PARCOM (1988), EEA (2001)). This measure is also provided by the OECD as a priority agri-environmental indicator, which accounts for nitrogen in- as well as output, in order to measure the net nitrogen input into the soil of a specific country. As mentioned in OECD (2008), "this calculation can be used as a proxy to reveal the status of environmental pressures (...)".

Obviously, the Nitrogen Balance is a theoretical concept and as such captures the potential nitrate pollution in a region. The question arises to which degree the indicator is capable of reflecting actual nitrate pollution effects (Sieling and Kage (2006), de Ruijter et al. (2007), Lord and Anthony (2002)). Investigating this issue is of pressing importance as OECD (2008) already draws attention to the fact that "Caution is required in linking trends in nutrient balances and environmental impacts, as the balances only reveal the potential for environmental pollution and are not necessarily indicative of actual resource depletion or environmental damage". So far much of the literature agrees that the Nitrogen Balance performs rather poorly when it comes to predicting observable nitrate pollution (Schroeder et al. (2004), Buczko et al. (2010), Sieling and Kage (2006), Rankinen et al. (2007), Korsaeth and Eltun (2000), Salo and Turtola (2006), Oenema et al. (2003)). Two important shortcomings of the cited works are that they usually concentrate on a narrow geographical area within a limited time frame and perform only simple correlation analysis without

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[1] Two measures are usually used to portray a nutrient balance, the farm-gate balance and the soil surface balance. In this paper, we focus on the Nitrogen Balance which is calculated according to the soil surface method concentrating on nitrogen in- as well as outputs as seen from the soil (Lord and Anthony (2002)).

controlling for other important exogenous variables.

De Ruijter et al. (2007) are among the very few to perform some regression analysis on this issue. Still, results concerning the appropriateness of the Nitrate Balance are mixed at best. Also, these works have very limited geographical as well as temporal scope and in general do not control for all relevant external factors. We believe the rigorous statistical analysis provided by this article will enrich the debate.

The paper is organized as follows. In the next section we introduce our data sources as well as data manipulations, the calculation of the Nitrogen Balance, descriptive statistics and methodological issues. The third section presents an econometric analysis of the determinants of nitrate concentration in groundwater, including a discussion on the effects of certain land covers, land uses and soil characteristics. In section four we once again employ econometric techniques to investigate the predicative power of the Nitrogen Balance by linking it with measured nitrate concentration levels in Austrian groundwater. Finally, section five offers some discussion on the results as well as conclusions.

2. Data, Calculations and Method

In the following section, we introduce our data and data sources. Also, we present the calculation of the Nitrogen Balance as well as some descriptive statistics. Finally, we briefly discuss the empirical methods used in the course of the analysis.

2.1. Data sources and manipulation

The concentration of nitrate in groundwater in mg/l is provided by the Umweltbundesamt (2010b). This data is available on a quarterly basis from 04/1991 to 04/2008 on municipality level in Austria. The cross section dimension consists of 1238 municipalities. We are presented with an unbalanced panel data set, i.e. nitrate concentration is not available for every time period in each of the municipalities. In the course of this analysis, we aggregate the quarterly values to annual average values for each municipality (*Nitrate*).

We further include data on precipitation in millimeter (*Precip*) and the maximum temperature in degree Celsius (*Temp*) provided on a daily basis for the years 1975 to 2007 by ZAMG (Zentralanstalt für Meteorologie und Geodynamik) (Strauss et al. (2009)). The weather observations stem from 34 weather stations, which we assign to the respective municipalities. We aggregate the weather observations to annual average values for each municipality.

Data on land cover in Austria are taken from the CORINE Land Cover database 2006 (Umweltbundesamt (2010a)). Land covers, such as buildings, cropland, meadows and forests have been computed as a proportion of total size of the municipality ($Landcover\_j$). In the short run, we assume land covers to be time-constant.

Detailed agricultural information on crop cultivation per cultivated crop, permanent grassland and amount as well as category of livestock is provided by the IACS (Integrated Administrative and Control System) database (BMLFUW (2010a)). The data is available on farm level on an annual basis for the years 1999 to 2008. The IACS database provides information on cropland (in hectares) for approximately 70 crops. We aggregate these crops into four crop groups: (i) oil seed and protein crops, (ii) cereal and maize crops, (iii) row crops and vegetables, and (iv) arable grassland. These groups are aggregated on municipality level and included into our regression models as proportion of total municipality territory ($Landuse\_j$). The sum of the proportion of permanent grassland and the proportion of cropland is referred to as agricultural land ($Prop\_AL$). The IACS database also provides information on whether conventional or organic farming systems are chosen on farm as well as annual level. Weighted by the size of the respective farm, we calculate the proportion of organic or conventional farming system per municipality. The resulting indicator ($Cult$) takes on a value between 1 and 2, where 1 represents the organic and 2 the conventional farming system.

Finally, we also integrate two indicators of soil quality into our analysis: Field water capacity (fwc) at 33 kPa in topsoil (cm3/cm3) and the volume of stones in topsoil (vs). Both variables are taken from the European digital soil map (Balkovic et al. (2007)) which provides several data entries per municipality. We aggregate these values on municipality level. Also in this case, it is reasonable to assume the values to be time-constant, at least over the short term. Both, "field water capacity" as well as "volume of stones" proxy for the ability of the soil to retain water. In particular, a high field water capacity implies less leaching. The volume of stones in topsoil is an indicator for the permeability of the soil.

2.2. Calculation of the Nitrogen Balance

Using the described data, we calculate the Nitrogen Balance on the municipality level according to the OECD and EUROSTAT Gross Nitrogen Balance Handbook (2007). The indicator is computed as total nitrogen inputs minus total nitrogen outputs.

Inputs to the Nitrogen Balance are (i) biological nitrogen fixation (nitrogen fixed in the soil), (ii) atmospheric deposition of nitrogen compounds, (iii) livestock manure,

and (iv) mineral fertilizer. Total nitrogen input is given by the sum of (i) through (iv).
The different input components are calculated as follows: The quantity of nitrogen fixed in the soil by symbiotic bacteria in kilogram nitrate on municipality level is calculated by multiplying the municipality's total area under cultivation (in hectare), by a Nitrogen fixation coefficient for a given crop in kilogram nitrogen per hectare. The coefficient is provided by ÖPUL[2] (OECD (2010)). The atmospheric deposition of nitrogen compounds in kilogram nitrate on municipality level is calculated by multiplying the utilized agricultural area by the nitrate deposition rate given in kilogram nitrate per hectare. The coefficient is provided by FEA[3] (OECD (2010)). The quantity of nitrogen excreted by livestock, used as organic fertilizer, is based on the number and category of livestock and calculated using the respective manure coefficient provided by ÖSTAT[4] (OECD (2010)).

Calculating the amount of applied inorganic fertilizer is more challenging. To this end, we use data on sales of ammonium nitrogen fertilizer for each of the nine Austrian provinces for the years 1998-2007 (except 2000) provided by the Grüner Bericht issued by the BMLFUW (2010b). To account for the total quantity of fertilizer applied in a municipality, we add the sales of inorganic fertilizer per province and the estimated quantity of nitrogen in livestock manure per province. The total quantities are then distributed among the municipalities within a province according to their hectare size of agricultural land. The sum of organic as well as inorganic fertilizer serves as a proxy of total fertilization ($Fert$).

Total nitrogen output includes most importantly withdrawals of harvested crop- and grassland commodities. To calculate the total production of crop- and grassland commodities, we rely on average yields per hectare per province as published in the Grüner Bericht (BMLFUW (2010b)), which are available for the years 2003 through 2008. The amount of nitrogen removed with harvested crop- and grassland commodities in kilogram nitrate is estimated by multiplying the crop and grassland production with commodity specific nitrate harvest coefficients provided by OECD (2010) ($Withd$).

Summarizing, computing total nitrogen input minus total nitrogen output allows us

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[2] Österreichisches Programm für eine umweltgerechte Landwirtschaft (Austrian Environmental Programme for Agriculture according to EU-Reg. 1257/99.)

[3] Federal Environment Agency

[4] Statistik Austria, vormals Österreichisches Statistisches Zentralamt (Austrian Central Statistical Office)

to estimate the Nitrate Balance ($NBal$) in kilogram nitrogen per hectare agricultural land on a municipality level for the years 2003 through 2007.

2.3. Descriptive Statistics

The detailed descriptive statistics can be found in Table 1 through Table 3. At this point, we would like to give a first graphical intuition of the ability of the Nitrogen Balance to predict environmental problems. Figure 1 shows the correlation of the annual average level of nitrate in groundwater in Austria (in mg/l) and the Nitrogen Balance (in 10.000 t). It is rather apparent that the trends are similar - a high Nitrogen Balance is correlated with relatively high levels of nitrate in groundwater and vice versa. Also, Figure 1 illustrates that there is a general downward trend in nitrate concentration of groundwater in Austria. The EU directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources sets the acceptable threshold of nitrate concentration in groundwater to 50 mg/l. This critical value is hardly ever reached in Austria. Nitrate concentration in the entire country has on average decreased over the past 18 years from 26 mg/l in 1992 to 21 mg/l in 2008. However, there is a high variation among the nine provinces of Austria. Nitrate concentration is traditionally low in the provinces of Salzburg, Tirol and Vorarlberg, whereas in the regions of Wien, Niederösterreich and Burgenland the content is very high.

2.4. Empirical Method

Given the panel structure of our data, we have the opportunity to employ a fixed effect panel analysis. In this kind of analysis, cross-section dummies are introduced to account for any time-constant cross-section (in our case municipality) specific effects (Baltagi (2001), Greene (2007)). Thus only time variation *within* the cross-section unit is used to estimate marginal effects. By construction, this method cannot provide us with estimations of effects of time constant variables, such as land cover or soil characteristics. Thus in what follows, we resort to the estimation method of pooled ordinary least squares (OLS) at some times. We use White standard errors to account for possible heteroscedasticity in the data. Also, standard errors are clustered by the cross-section dimension to account for the fact that observations of one particular municipality over a period of time are not independent (Wooldridge (2001)). We decided for this approach in favor of the so-called Between Estimator. The Between Estimator takes care of the potential serial correlation but averages over time periods, such that valuable information is lost.

In the following section on the determinants of nitrate levels in groundwater we only resort to pooled OLS analysis, since land cover and soil characteristics are assumed to be constant over time. To analyse the predictive power of the Nitrate Balance in section 4, we use a fixed effect estimation. At a later point in that section, when also accounting for soil qualities, we resort back to a pooled OLS estimation.

3. Determinants of nitrate concentration in groundwater

In this section, we investigate the determinants of the nitrate level in groundwater. In particular, we focus on the role of precipitation, temperature, different types of land cover, specific soil characteristics and differing crop cultivation choices in explaining the concentration of nitrate in groundwater. As mentioned, some of the explanatory variables exhibit little or no variation over time, so that a clustered pooled OLS analysis is the most appropriate analytical tool to explain the variation of nitrate concentration over years and municipalities. To allow for non-linear effects of the explanatory variable, we occasionally include squared terms in the regression equations.

3.1. Site specific characteristics

We investigate the relationship between nitrate concentration in groundwater and various site specific characteristics such as land cover, weather conditions and soil quality. The time dimension (t) is given by years, the cross-sectional dimension (i) represents municipalities. Dummies ($Year$) are included to control for aggregate annual shocks[5].

The regression equation takes the form

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[5] Year dummies are defined as follows:

$$\begin{aligned} YEAR_{kt} &= 1 \quad if \quad k = t \\ &= 0 \quad otherwise \end{aligned}$$

$$\begin{aligned} Nitrate_{it} = \beta_0 + \beta_1 Precip_{it} + \beta_2 Temp_{it} + \beta_3 Cult_{it} + \sum_j \beta_{4j} Landcover\_j_i \\ + \sum_j \beta_{5j} Landcover\_j_i^2 + \beta_6 fwc_i + \beta_7 vs_i + \sum_k \beta_{8k} Year_{kt} + \varepsilon_{it} \qquad (1) \\ \text{where} \quad j \,\epsilon\, \{\text{buildings}, \text{cropland}, \text{grassland}, \text{forest}\} \\ \text{and} \quad k \,\epsilon\, \{1992, ..., 2008\} \end{aligned}$$

Precipitation is conjectured be important role in explaining the variation in nitrate contents. Schweigert et al. (2004) found that the average September precipitation may lead to higher nitrate leaching. Extending this reasoning towards the effect of precipitation on nitrate concentration in groundwater, we conjecture that increasing precipitation might affect nitrate concentration in groundwater positively (Korsaeth and Eltun (2000), Rankinen et al. (2007)). Pardeller (1996) suggests that high levels of precipitation can either accelerate the leaching of nitrate excess into groundwater, but could also support the dilution of nitrates. In addition, higher average precipitation may foster the uptake of nitrogen by crops (Schweigert et al. (2004)). Consequently, the coefficient of precipitation could have a negative or a positive sign.

Another weather effect of importance is the annual average maximum temperature. On the one hand, the maximum temperature controls for the geographical location of the municipalities. Alpine municipalities (mostly located in the provinces of Salzburg, Tirol or Kärnten) have - due to their altitude - an average annual maximum temperature lower than the Austrian average. As there is less agricultural activity at high altitudes, one would expect lower nitrate concentrations in these regions. On the other hand, high temperatures favor evapotranspiration, such that less nitrate leaches into groundwater. Also, the mineralization rate in the soil is affected by temperature. On the one hand, higher temperatures can lead to higher mineralization rates, whereas this process is on the other hand reduced by dryness (Schweigert et al. (2004)).

Concerning the different types of land cover, we expect a clear positive effect of the proportion of cropland on nitrate (Schroeder et al. (2004)), since higher fertilization rates may lead to excesses, which can leach into groundwater. Conversely, we expect meadows and forests to have a negative impact on nitrate concentration. Additionally, we expect the proportion of buildings in a municipality to have a positive effect on nitrate concentration. We also expect the sign of the estimated coefficient on field water capacity to be negative, because a higher field water capacity implies less leaching. Contrarily, a higher proportion of stones in the soil might affect the nitrate content in groundwater positively, since a higher content of stones makes the soil more permeable (Buczko et al. (2010)).

The results of estimation equation (1) are depicted in Table 5. Our findings indicate that average precipitation as well as the average maximum temperature impact negatively on nitrate concentration.

Municipalities where precipitation levels are high experience lower nitrate levels in groundwater. This result points to some kind of dilution effect of precipitation. In particular an increase of average daily precipitation levels of 1 millimeter implies, ceteris paribus, a decrease of observed average nitrate concentration in groundwater by 0.84 milligram per liter. If we compare a municipality with average daily rainfall (2.78 millimeter) with one that experiences maximum rainfall (a daily average of 10.8 millimeter), our estimate implies that, ceteris paribus, the nitrate concentration in the municipality with higher rainfall is lower by 6.75 milligram per liter. Considering that the average nitrate concentration level is around 20 milligram per liter, this implies a large impact of precipitation.

The average maximum temperature equally exhibits a negative effect on nitrate concentration, which suggests that in municipalities with higher temperature, higher evapotranspiration rates and biomass production takes place that in turn reduces leaching of nitrate into groundwater (Schweigert et al. (2004)). The difference between the municipalities with the highest average temperature (that is the difference between the observed maximum and the minimum) is 20.3 degree Celsius. This implies, ceteris paribus, a decrease in nitrate content of groundwater of 12.9 milligram per liter, again a sizable result.

Note that this analysis is performed on the largest possible data set (that is including the years 1992 through 2008). The findings for precipitation and temperature are confirmed in all results, such that the qualitative observations with respect to precipitation and temperature seem especially robust, though varying in magnitude as the used data sets vary in size.

In addition, we find statistically significant non-monotonous effects of all land cover types: Cropland has an exponential positive effect on nitrate concentration, as expected. The contrary is found for the proportion of meadows as well as buildings, for which initially a negative effect on nitrate concentration is found, but which seems to weaken with increased coverage. Finally, high forest coverage has a negative effect on nitrate concentration.

Also, soil quality is important when it comes to explaining nitrate content in groundwater. The effect of the field water capacity on nitrate content is, as expected, negative. The higher the capacity of the soil to retain water, the less fertilizer leaches into groundwater. On the other hand, the content of stones in topsoil has a positive effect, confirming our assumption that soil with high stone content favors the leaching of nitrate into groundwater.

3.2. Land use and farming systems

Observing the positive effect of cropland, we investigate the degree to which particular crop types are related to nitrate concentration in groundwater. Regression (2) estimates a model of the form

$$\begin{aligned} Nitrate_{it} &= \beta_0 + \beta_1 Precip_{it} + \beta_2 Temp_{it} \\ +\beta_3 Cult_{it} + \sum_j \beta_{4j} Landuse\_j_i + \beta_5 fwc_i + \beta_6 vs_i &+ \sum_k \beta_{7k} Year_{kt} + \varepsilon_{it} \quad (2) \\ &\text{where} \\ j \,\epsilon\, \{\text{oil seed \& protein, arable grass, cereal \& maize, row crops \& veg, grassland}\} \\ \text{and} \quad k \,\epsilon\, \{1999, ..., 2008\} \end{aligned}$$

As discussed, we classify crop types into four groups: oilseed & proteins, arable grassland, cereal & maize, and row crops & vegetables, expecting the coefficients of the various crop categories to be positive. Additionally, we control for the relative amount of grassland, the farming system (organic or conventional) in each municipality. We expect nitrate concentration in groundwater to increase with higher proportions of conventional farming systems.

The results are reported in Table 5. Estimating equation (2), we find that all crop types exert a statistically significant positive effect on nitrate contamination of groundwater, except the proportion of arable grassland. Also, we find that municipalities with more conventional farming systems experience significantly higher levels of nitrate in groundwater. This is expected, due to more intense use of mineral fertilization in conventional agriculture. In particular, comparing a municipality that exclusively produces crops organically with one that produces conventionally, we find, ceteris paribus, an increased nitrate level of almost 3 milligram per liter in the latter one. The relative amount of grassland, precipitation, maximum temperature and soil characteristics are found to be significant with the same signs as previously discussed.

4. The Nitrogen Balance Indicator and Actual Pollution

The Nitrogen Balance is often used to capture environmental pressures on soil, water and air originating from nitrate surpluses. As a theoretical concept, it can only reflect the potential of environmental pressures. Disposing of detailed data on actual nitrate contamination (that is the amount of nitrate in groundwater), we are able to link potential pollution (as reflected by the Nitrogen Balance) to actual pollution.

4.1. Fixed Effects

For a first impression as to how well the Nitrogen Balance and its components respectively capture nitrate content in groundwater we consider a fixed effect panel estimation, where dummies for each municipality control for site-specific characteristics such as soil quality, which are time-constant over the short term. The following equations are estimated for the years for which the Nitrogen Balance could be calculated (i.e. 2003-2007):

$$Nitrate_{it} = \alpha_i + \beta_0 + \beta_1 Precip_{it} + \beta_2 Temp_{it} + \beta_3 NBal_{it} + \varepsilon_{it} \tag{3}$$

$$\begin{aligned} Nitrate_{it} = \alpha_i + \beta_0 + \beta_1 Precip_{it} + \beta_2 Temp_{it} + \beta_3 Fert_{it} \\ + \beta_4 Withd_{it} + \varepsilon_{it} \end{aligned} \tag{4}$$

The results (Table 5) indicate that the Nitrogen Balance is a suitable indicator to predict actual environmental pollution. High values of the indicator are associated with high nitrate concentration in groundwater. Quantitatively though, the Nitrate Balance explains relatively little of observed nitrate concentration in groundwater. The estimated coefficient of β_3 implies that an increase of the average Nitrate Balance indicator by 10 kilogram nitrate results in an increase of only 0.35 milligram per liter in nitrate concentration of groundwater.

Taking a closer look at the composition of the indicator, we also assess the effect of its separate components. For reasons of multicollinearity, we concentrate on the measure of fertilization (nitrogen input) as well as withdrawal by harvested crops and forage (nitrogen output). As expected, we find a positive influence of nitrogen input and a negative one of nitrogen output on observed nitrate concentration. Also weather related factors are important in explaining nitrate concentration in groundwater, as already discussed in the previous section.

4.2. Accounting For Fixed Effects

As a next step, we account for the fixed effects of the previous regressions by including several site-specific characteristics, such as the proportion of agriculturally used land, soil quality and farming systems of the respective municipality. We therefore estimate the following regression equations using the technique of clustered pooled OLS:

$$\begin{aligned} Nitrate_{it} = \beta_0 + \beta_1 Precip_{it} + \beta_2 Temp_{it} + \beta_3 PropAL_{it} + \beta_4 Cult_{it} \\ + \beta_5 NBal_{it} + \beta_6 fwc_i + \beta_7 vs_i + \sum_k \beta_{8k} Year_{kt} + \varepsilon_{it} \\ \text{where} \quad k \,\epsilon\, \{2003, ..., 2007\} \end{aligned} \tag{5}$$

Including site-specific characteristics is especially valuable within our analysis since it allows us to assess whether the Nitrogen Balance performs better as a proxy for actual environmental pollution once these characteristics are taken into account. In particular, some of these variables might play an important role in determining the predictive power of the Nitrogen Balance. To test this hypothesis, we introduce interaction terms into the regression equation:

$$\begin{aligned} Nitrate_{it} = \beta_0 + \beta_1 Precip_{it} + \beta_2 Temp_{it} + \beta_3 PropAL_{it} + \beta_4 Cult_{it} + \beta_5 NBal_{it} \\ + \beta_6 fwc_i + \beta_7 vs_i + \beta_8 Feat_{it} \cdot NBal_{it} + \sum_k \beta_{9k} Year_{kt} + \varepsilon_{it} \\ \text{where} \quad k \,\epsilon\, \{2003, ..., 2007\} \end{aligned} \tag{6}$$

The variable $Feat$ captures characteristics, such as precipitation, temperature, farming systems, volume of stones or field water capacity. The results of several regressions of the form (6) respectively demonstrate that of all exogenous factors only precipitation is crucial when determining the explanatory potential of the Nitrogen Balance (Table 5). If high average precipitation is observed, the Nitrogen Balance does particularly well in predicting environmental problems, that is the marginal effect of the indicator is significantly influenced by the level of precipitation[6].

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[6] The marginal effect of the Nitrate Balance in the nitrate level in groundwater in this specification is given by

$$\frac{\partial Nitrate}{\partial NBal} = \hat{\beta}_5 + \hat{\beta}_8 \cdot Precip$$

The marginal effect is positive if $Precip > 0.75$, which is always the case, corroborating the results discussed in Section 4.1.

Since the indicator captures the theoretical potential for environmental pressure, it seems that the degree to which this potential translates into actual contamination depends significantly on the amount of precipitation (Sieling and Kage (2006)). This is rather intuitive considering the leaching effect. Assuming the Nitrogen Balance captures the pressure of nutrient surpluses on the soil, the degree to which this translates into nutrient contamination of groundwater is determined by the degree of the leaching effect. The leaching effect in turn is stronger, the higher precipitation (Rankinen et al. (2007))[7].

Concluding, these results suggest that an indicator that wishes not only to portray the potential damage to the environment from nitrate pollution but also the actual environmental degradation in a region, should take into account specific environmental conditions, in particular the amount of precipitation.

5. Discussion and Conclusion

As an important input for agricultural production, nitrogen puts environmental pressure on (ground)water, soil and air. In this article, we identify the likely determinants of nitrate contamination of groundwater. We find that increased agricultural activity (especially if crops are conventionally cultivated) leads on average to higher nitrate concentration in groundwater. Additionally, environmental factors such as precipitation and temperature play an important role. Higher average temperature leads to lower nitrate pollution of groundwater possibly due to increased evapotranspiration. Equally, higher average precipitation dilutes nitrate contents, reducing nitrate concentration in groundwater. Thus, we point out activities that are most harmful to observed environmental outcomes and should therefore be in the center of attention when considering direct regulation policies.

Nitrate pollution from agricultural land uses is usually considered to be a non-point source pollution problem. Therefore the specific polluter is hard to identify and the level of pollution strongly depends on stochastic processes (e.g. weather events) and spatial attributes (e.g. soil quality, topography, land use) leading to diffuse impairments of groundwater aquifers. Consequently, indicators are required that

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[7] Note that even though $\hat{\beta}_8$ is positive the overall marginal effect of precipitation given by

$$\frac{\partial Nitrate}{\partial Precip} = \hat{\beta}_1 + \hat{\beta}_8 \cdot NBal$$

is - on average - negative.

establish the functional relationship between pollution and agricultural activity in the context of site characteristics to allow effective policy regulation.

The Nitrogen Balance has been identified by the OECD as a priority agri-environmental indicator, meant to measure the potential damage to the environment through nitrate excess. Having identified the direct determinants of nitrate pollution, we find much support for the appropriateness of the variables used in the calculation of this indicator. Cropland exerts a strong positive effect, corroborating the notion underlying the calculation of the Nitrogen Balance, that fertilization is a major source of nitrate contamination.

The second contribution of this work lies in assessing the explanatory power of the Nitrogen Balance when it comes to measuring actual pollution levels, such as nitrate concentration in groundwater. In our econometric analysis, we find that the indicator exerts a positive influence on nitrate levels in groundwater, and thus conclude that it is a good predictor for environmental pollution.

In addition, we investigate if the explanatory power of the indicator can be improved once weather conditions or soil qualities are accounted for. In particular we find that, the higher average precipitation in the region, the more useful is the indicator as a predictive tool. Our analysis suggests that the indicator should be enriched with these site characteristics if its purpose is to predict actual environmental pollution. This idea is also supported by the quantitatively relatively small effect of the Nitrate Balance on observed nitrate pollution, discussed in Section 4.

This finding calls for a more sophisticated approach, which becomes especially relevant once the Nitrate Balance is used as an indicator to design and evaluate environmental policy by, for example, imposing standardized threshold countries have to comply with. This fact has also been recognized by other scholars (Buczko et al. (2010), Schroeder et al. (2004), Lord and Anthony (2002)). Schroeder et al. (2004) for example note that "Even within one and the same farm type and crop type, similar inputs may result in different outputs, due to variation to husbandry techniques, crop characteristics, soil, climate and management". Also de Ruijter et al. (2007) mention that it depends critically on the drainage potential of soils how nitrate surplus in soils translates to nitrate contamination of groundwater. Thus, the maximum feasible amount of nitrogen which does not impede "good groundwater quality" critically depends not only on agricultural activities but also on external factors.

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Table 1: Summary Statistics for Austria. Measurement units see Table 4. Variables 1-5 for the years 1999-2008; Variables 6-7 are time constant.

	Variables	Obs.	Mean	Stddev
1	$Cult$	9228	1.868	0.213
2	$Landuse\_oilseed\&protein$	9974	0.376	0.037
3	$Landuse\_arablegrass$	7856	8.631	4.081
4	$Landuse\_cereal\&maize$	7856	23.283	2.334
5	$Landuse\_rowcrops\&veg$	7856	2.518	0.769
6	fwc	1028	0.031	0.041
7	vs	1028	0.042	0.04

	Province	Obs.	Landcover_grassland		Landcover_cropland		Landcover_buildings		Landcover_forest		PropAL (IACS)		
			Mean	Stddev.	Mean	Stddev.	Mean	Stddev.	Mean	Stddev.	Obs	Mean	Stddev.
1	BURGENLAND	75	0.012	0.023	0.547	0.234	0.069	0.048	0.276	0.199	758	0.589	0.303
2	KÄRNTEN	77	0.075	0.070	0.082	0.125	0.044	0.049	0.644	0.165	717	0.302	0.137
3	NIEDERÖSTERREICH	247	0.033	0.091	0.496	0.290	0.100	0.117	0.257	0.215	2538	0.598	0.303
4	OBERÖSTERREICH	159	0.109	0.144	0.267	0.277	0.090	0.131	0.301	0.240	1704	0.532	0.237
5	SALZBURG	71	0.263	0.219	0.001	0.005	0.066	0.090	0.594	0.259	601	0.466	0.535
6	STEIERMARK	218	0.077	0.083	0.153	0.185	0.104	0.147	0.515	0.221	1915	0.331	0.190
7	TIROL	143	0.121	0.113	0.008	0.031	0.070	0.089	0.718	0.180	1393	0.321	0.285
8	VORARLBERG	37	0.111	0.103	0.055	0.107	0.181	0.182	0.554	0.319	338	0.397	0.237
9	WIEN	1	0.004	.	0.115	.	0.626	.	0.179	.	10	0.160	0.022
10	AUSTRIA	1028	0.087	0.126	0.242	0.289	0.090	0.121	0.447	0.279	9974	0.460	0.306

Table 2: Summary Statistics of proportion of various land types across province; *Landcover_grassland, Landcover_cropland, Landcover_buildings* and *Landcover_forest* taken from CORINE land cover database 2006, constant across years; *PropAL* taken from IACS database, average for years 1999-2008.

Table 3: Summary Statistics over the period 2003-2007 of the Nitrogen Balance in kg per ha, fertiliser in kg per ha, and nitrogen withdrawal in kg per ha

	Province	Obs.	*Nbal*		*Fert*		*Withd*	
			Mean	Stddev.	Mean	Stddev.	Mean	Stddev.
1	Burgenland	381	7.74	4.72	48.23	3.05	71.89	6.88
2	Kärnten	377	30.3	6.1	74.1	3.71	92.29	5.26
3	Niederösterreich	1266	32.02	3.16	91.79	4.61	91.98	6.16
4	Oberösterreich	852	60.17	9.01	143.99	9.37	126.53	3.74
5	Salzburg	300	20.41	5.7	57.11	4.67	83.47	3.4
6	Steiermark	964	62.03	4.79	125.75	6.54	106.01	4.74
7	Tirol	692	21.54	5.84	38.09	4.56	63.48	5.2
8	Vorarlberg	188	16.72	7.8	46.08	8.61	75.23	4.85
9	Wien	5	22.02	6.41	60.5	3.47	60.9	9.07
10	Austria	5025	37.16	3.17	92.43	5.41	94.92	3.98

Table 4: Data description

Variable	Description	unit	source
Nitrate	annual average content of nitrate in groundwater per municipality	in mg/l	Umweltbundesamt (2009)
Precip	annual average amount of precipitation per municipality	in mm	ZAMG (Strauss et al. 2009)
Temp	annual average maximum temperature per municipality	in řC	ZAMG (Strauss et al. 2009)
vs	average volume of stones in the topsoil per municipality	in %	European digital soil map (Balkovic et al., 2007)
fwc	average field water capacity at 33 kPa in the topsoil in the topsoil per muncipality	cm3/cm3	European digital soil map (Balkovic et al., 2007)
NBal	Gross Nitrogen Balance in kg/ha per municipality	in kg/ha	own calculation according to OECD Handbook (2007)
Fert	Total amount of Fertiliser in kg/ha per municipality	in kg/ha	own calculation according to OECD Handbook (2007)
Landuse_grassland	Proportion of grassland per municipality	in %	CORINE Land Cover database 2006
Landuse_crops	Proportion of cropland per municipality	in %	CORINE Land Cover database 2006
Landuse_buildings	Proportion of buildings per municipality	in %	CORINE Land Cover database 2006
Landuse_forest	Proportion of forest per municipality	in %	CORINE Land Cover database 2006
PropAL	Proportion of agricultural land per municipality	in %	IACS database (1999-2008)
Landcover_oilseed&proteins	Proportion of oilseed and protein crops per municipality	in %	IACS database (1999-2008)
Landcover_arablegrass	Proportion of arable grass per municipality	in %	IACS database (1999-2008)
Landcover_cereal&maize	Proportion of cereal and maize per municipality	in %	IACS database (1999-2008)
Landcover_rowcrops&veg	Proportion of rowcrops and vegetables	in %	IACS database (1999-2008)
Cult	weighted indicator for organic/ conventional cultivation per municipality	1 (org.)- 2(conv.)	IACS database (1999-2008)

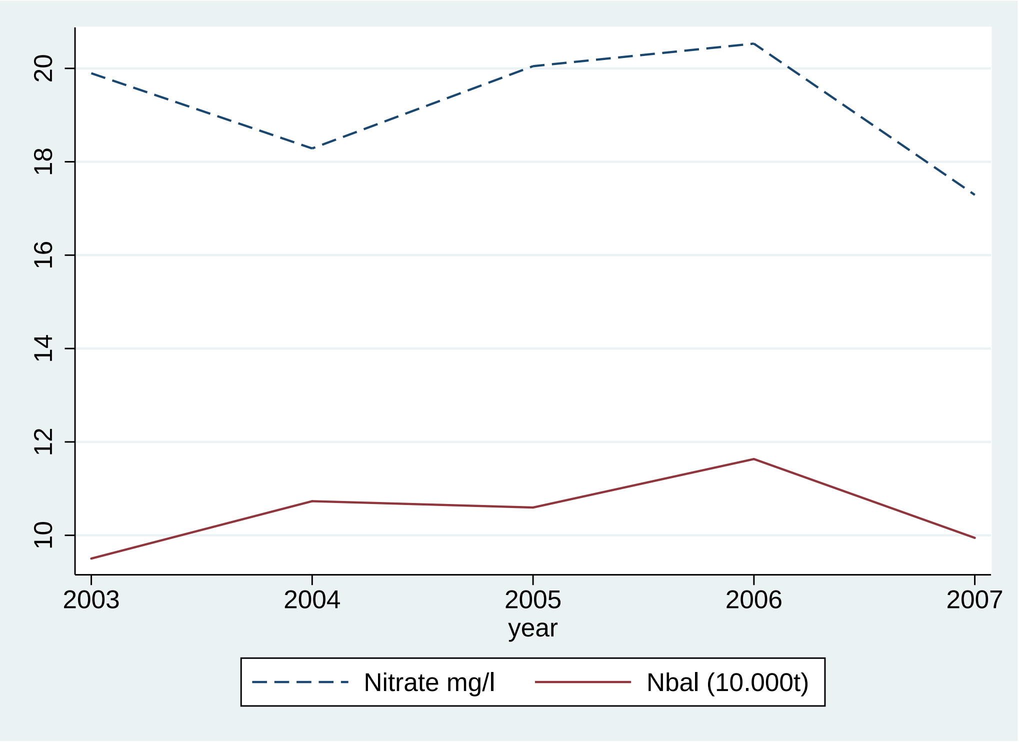

Figure 1: Average nitrate concentration (in mg/l) in Austrian groundwater and the Nitrogen Balance (in 10.000 t)

Table 5: Results of the regression analysis

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent Variable:	$Nitrate$	$Nitrate$	$Nitrate$	$Nitrate$	$Nitrate$	$Nitrate$
$Precip$	-0.838***	-0.649**	-0.274***	-0.286***	-2.287***	-3.546***
$Temp$	-0.635*	-1.022***	-0.257***	-0.246***	-1.310***	-1.294***
$Landcover\_grassland$	-19.91**					
$Landcover\_grassland^2$	27.06**					
$Landcover\_cropland$	11.73					
$Landcover\_cropland^2$	40.83***					
$Landcover\_buildings$	-18.12					
$Landcover\_buildings^2$	41.29*					
$Landcover\_forest$	44.91***					
$Landcover\_forest^2$	-51.68***					
fwc	-71.26***	-104.5***			-203.3***	-202.7***
vs	0.445***	0.119			0.164	0.175
$Cult$		2.949*			6.149***	5.708***
$Landuse\_oilseed\&protein$		65.60*				
$Landuse\_arablegrass$		24.21				
$Landuse\_cereal\&maize$		24.61***				
$Landuse\_rowcrops\&veg$		56.63**				
$Landuse\_grassland$		-15.94***				
$Nbal$			0.0347***		0.0654***	-0.0275
$Fert$				0.0350***		
$Withd$				-0.0261**		
$Prop\_AL$					18.36***	18.28***
$Precip * Nbal$						0.0366**
$Constant$	43.27***	60.39***	20.17***	20.59***	95.52***	98.94***
Observations	14169	7036	4811	4811	4423	4423
Adjusted R-squared	0.289	0.297	0.949	0.949	0.240	0.242

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

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