Soil and terrain attributes for evaluation of leaching in a Montana farm field
by Melissa Ann Landon

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Soils
Montana State University

Abstract:
Degradation of water quality from agricultural sources is a critical concern for both surface and ground waters in the United States. Nutrient (nitrate) management on the farm can reduce agricultural non-point pollution. Practical and operational solutions to ground water contamination problems will require consideration of contrasting environmental differences within fields. One difficulty in designing leaching models is that when a model successfully simulates a particular profile, it may not be representative of the overall field situation due to spatial and/or temporal variability.

The objectives of this study were to: 1) characterize the spatial variability of nitrate and bromide leaching; 2) test the leaching prediction capabilities of several soil, soil water, and terrain attributes that singly, or in combination, represent the spatial distribution of soils and microclimate in a farm field under uniform application of nitrogen and bromide; and 3) determine if a topographically-derived wetness index is correlated with field-measured soil water content. Nitrogen was applied by the farmer in the course of normal field management and potassium bromide was uniformly applied to small areas at 70 selected sites. Soil samples were collected at each site to a maximum depth of 180 cm every spring and fall for three years (two cropped, one fallow).

Small spatial variability in soil water (to 25 cm, 100 cm and 150 cm depths) was measured. It is possible that the thick, permeable, loess-derived soils capture and retain precipitation from rainfall and melting snow without significant lateral distribution in the landscape. The observed variability in solute concentrations was also small and less than reported in other field studies. The spatial variability of bromide increased over time indicating that movement (leaching) differences may be expressed slowly. Paired t-tests and correlation analyses indicated that the spatial behavior patterns of nitrogen and bromide were similar in only two of five time periods.

Three types of leaching indices were calculated for both nitrogen and bromide. Stepwise multiple regression analysis occasionally showed some promise, but the results were not consistent. None of the three index types produced results more reliable or consistent than the other two. Exclusion of sites within an ephemeral stream channel also did not produce substantially or consistently better results. Overall, nitrogen leaching indices produced slightly stronger relationships with the environmental factors than bromide indices.

Correlation analysis indicated that wetness indices at two scales (2 m and 10 m) were moderately correlated to one another and to the thickness of the mollic horizon. Neither the wetness indices or thickness of mollic horizon were correlated to either season average measured water content or average measured water content from June of each year.

These results reiterate the difficulties that are encountered in trying to understand (predict) the interrelationships between environment, nitrogen leaching, and potential contamination of ground water.

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ABSTRACT

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CHAPTER 1

SITE-SPECIFIC FARMING, NITRATE LEACHING, AND GROUND WATER QUALITY

Background

Nitrate Leaching and Ground Water Quality

Ground water is the source of public drinking water for nearly 75 million people in the United States. Private wells supply water to an additional 30 million individuals. Evidence indicates that contaminants from agricultural production are now found in underground water supplies (National Resource Council, 1989). Major water quality problems of concern to agriculture are nutrients, pesticides, and sediments. Nutrients and pesticides in water supplies can be a health concern when levels reach established critical levels.

Non-point sources of pollution have been difficult to identify and regulate (Bauder et al., 1991), but nitrogen (N) has received the most attention as a threat to water quality. Nitrite is the most toxic form of N, but children, young animals, and cattle convert nitrates into nitrites in their stomachs and can develop methemoglobinemia. In 1962, the U.S. Public Health Service set an upper limit on nitrate in drinking water at 10 mg NO_3-N per liter (45 ppm nitrate) (McCool and Renard, 1990). In 1991, Bauder et al. found in a study of private well water quality in Montana that 1 in every 20 samples had nitrate-N concentrations greater than the U.S. EPA standard of 10 parts per million. Fifty percent of the high nitrate samples were attributed to point-source contamination. The other 50% may be the result of long-term summer fallowing.

Nitrates in ground water originate from several non-point sources, including geological substrate, septic tanks, improper use of animal manures, cultivation (especially fallowing), precipitation (acid rain), mineralization of organic N, and fertilizers (Power and Schepers, 1989). Most nitrate-related environmental impacts occur at local or regional scales rather than the national scale, and they usually mimic spatial distribution of the sources (National Research Council, 1978). Conditions conducive to ground water contamination by fertilizer include shallow ground water, coarse-textured soils, low organic matter levels, high soil permeability, and excess water (precipitation, irrigation) (Follett et al., 1991).

Since the late 1960's, there has been a three-fold increase in applications of N to Montana soils (Jacobsen and Johnson, 1991). Under native prairie vegetation, annual N inputs were typically measured in tens of kg ha^{-1}. Today, inputs of several hundred kg N ha^{-1} are common with many grain crops (National Research Council, 1978). However, most plants apparently cannot remove all of the NO_3-N present in soil solution. Numerous field studies have shown that less than 50% of the N input into grain crops is removed in the harvested crop. Therefore, 100 kg N ha^{-1} or more is either stored in the soil or lost into the environment (National Research Council, 1978).

Nitrate is the end product of the reactions converting other forms of N in soil. It is stable and remains in soil once it has been introduced, except when removed by plant uptake, denitrification, or leaching. The quantity of N available to plants is a function of the amounts applied as manure and fertilizer and mineralized from soil organic matter. Only a small fraction (usually <1%) of the total N in surface soils is present as nitrate, but this fraction can undergo rapid changes depending on both environmental conditions and external sources. Moisture and temperature are major factors affecting the amount of nitrate in soil, and the nitrate concentrations vary seasonally, often in a complicated and unpredictable fashion (National Research Council, 1978). The amount of N released from organic sources, and to some extent, the amount of fertilizer-derived N existing in the soil after addition of ammonium (NH^{4+}) or nitrate (NO^{3-}) depends on the factors affecting N mineralization, immobilization, and losses from the soil. Nitrogen fertilizers applied in any form are converted to nitrate through nitrification. During the growing season, nitrate is absorbed rapidly by plant roots, probably by a combination of active (metabolic) and passive (water flow) mechanisms.

Nitrate losses from soil are typically measured utilizing ceramic cups, lysimeters, collecting water from field drainage, or sampling soil rather than water, or estimated by computer modeling (Addiscott et al., 1991). The rate of nitrate leaching from the soil depends on a wide variety of factors. Nitrate leaching from soil is affected by: plant cover (Hill, 1991), rainfall or irrigation (Thomas, 1970), temperature (National Research Council, 1978), soil texture and organic matter content (Bergstrom and Johansson, 1991), soil depth, structure and parent material (Hill, 1991), ground water level and drainage (Hill, 1991), crop strains, tillage (National Research Council (1978), and forms of N (Hill, 1991).

Nitrate distribution in a soil system is a function of the water balance of the soil system in that rainfall and irrigation move nitrate downward, while evaporation moves nitrate back towards the surface. However, the evaporative process is usually important only in the upper 30 cm of the soil profile (Thomas, 1970). Temperature is a factor because water drains more slowly through cold soils. Freezing essentially stops downward nitrate movement (National Research Council, 1978). Soil texture and organic matter content can have a major influence on leaching (Bergstrom and Johansson, 1991). Light and sandy soils tend to retain less water than heavy clay soils and, therefore, allow more free movement of water and soluble ions following rainfall. Shallow soils are also usually well drained and are associated with rapid leaching. Soils rich in organic matter are usually also rich in organic N. This provides suitable material for the bacterial formation of nitrate and subsequent nitrate leaching. Tillage stimulates ammonification and nitrification, and most row cropping practices leave the land bare at least part of the year (National Research Council, 1978). A vegetation-free period and high rainfall can lead to an increased downward movement of nitrate into aquifers (Hill, 1991).

Spatial Variability of Soil and Water Properties

Most of the soil and environmental parameters which influence the transport of dissolved nitrates through natural fields vary substantially at different locations, even at short separation distances, and many are not normally distributed (Addiscott and Wagenet, 1985). Spatial and temporal variability in soil properties with depth in the soil profile and across landscape positions results in diverse patterns of water and solute distribution in the landscape. Beckett (1987) points out that the temporal variability of soil nutrient status may equal or exceed spatial variability.

Hall and Olson (1991) state that two categories of variability, systematic and random, exist in most landscape studies. Placement in either category may depend on the level or scale of observation. Soil profile depth, water content, and soil physical and chemical properties vary with landscape position (Daniels et al., 1985; Brubaker et al., 1993). This systematic variation of soil properties with landscape position may affect solute transport under natural rainfall conditions (Afyuni et al., 1994).

Bouma and Finke (1993) alternatively suggest that soil variability may be attributed to natural soil resource variability or management-induced variability. Soil resource variability can be expressed in terms of static and dynamic properties. Static properties are those that, for example, relate to variation in relatively stable soil properties such as soil texture or organic matter content. Dynamic properties are those that exhibit differences at short distances; for example, water, solute, air, and temperature regimes.

Soil textural and structural properties, antecedent soil water content distributions, and the rate and amount of infiltrating water affect leaching and movement of water and solutes (Anderson and Bouma, 1977a;1977b). Even when the water application rate is relatively uniform over the entire soil surface, such as with rainfall (Jury et al., 1982) or sprinkler irrigation (Van de Pol et al., 1977; Butters, 1987), the resulting vertical water velocities within the soil are not spatially uniform. Lateral movement can cause substantial variations in solute concentration across a field of agricultural size (Jury and Nielsen, 1989).

Soil hydraulic properties vary across landscape positions due to changes in soil profile characteristics (Bathke and Cassel, 1991). Nielsen et al. (1994) state that the soil hydraulic conductivity at water saturation is 10 million times greater than that exhibited at air-dryness or, stated another way, a seven percent change in soil water content yields a corresponding 10-fold change in hydraulic conductivity. Therefore, small differences in soil water content across a seemingly uniform field soil lead to large differences in the rate of movement of water (and its dissolved constituents) through the soil.

Site-Specific Farming

Concerns for agricultural sustainability and for protection of surface and ground water from agricultural chemicals has resulted in increased interest in precision or site-specific farming. The modern implementation of site-specific crop management is often thought of in terms of the integration of two complementary technologies: GPS and GIS. GPS, the satellite-controlled Global Positioning System, provides the location coordinates for recording data and controlling devices in the field. GIS (Geographic Information Systems) maintain geographically correct linkages between GPS-generated data from the field and desktop mapping and decision support applications (Brown and Saufferer, 1991).

In order for a computer simulation model of field-scale leaching to have practical application in this context, computer programs capable of identifying best combinations of management practices for a given soil, climate, and water regime must be developed. Precise guidance of equipment (relative to a previously defined position) is now possible due to the 24-hour availability of NAVSTAR GPS satellites and receivers capable of determining position in real time with a resolution of one centimeter (Larson et al., 1991). In addition to these guidance systems, field implementation of these management practices benefit from: 1) mechanisms (i.e., sensors on field equipment) to detect differences within a field with respect to important soil properties (texture, organic matter, bulk density, water content, temperature, nutrient status, etc.); and 2) servo-mechanisms controlled by an on-board computer to alter settings on planters, tillage tools, sprayers, fertilizer spreaders, cultivators, and other machinery while moving through the field.

Within such a system, a farmer could maintain or enhance crop yield, optimize fertilizer and other inputs, maximize net return, and also potentially control ground water contamination or other environmental problems (Power and Schepers, 1989). Preliminary field experiment results from a soil specific anhydrous ammonia management system in Minnesota indicate variable benefits, with a maximum of $17 ha^{-1}, when comparing soil specific management to conventional soil management (Robert, 1991). In 1991, Macy realized a $5.67 ha^{-1} savings on a 54 ha field in Wayne County, Indiana utilizing spatially variable control of fertilizer and seed.

Carr et al. (1991) used yield and fertility trials in 1987-88 at five locations to demonstrate that fertilizing by soil is profitable under dryland systems in Montana.

On-Farm, Field-Scale Information Systems

Many technologies necessary to implement site-specific crop management practices are currently being developed as separate and narrowly focused, dedicated applications. Brown and Saufferer (1991) state that unless these "closed subsystems" can be networked into a whole-farm, integrated management information system, their potential value will be greatly limited.

There is a growing demand for simple techniques applicable for day-to-day land management decisions, but which also incorporate environmental protection considerations. To that end, integrated technological systems including on-farm, field-scale information systems and site-specific farming provide opportunities for "farming soils, not fields" (Carr et al., 1991). Implementation of integrated agricultural management practices can have two major consequences: 1) effects on the environment including ground water quality; and 2) effects on economic return from the agricultural enterprise (Power and Schepers, 1989).

Field-Scale Solute Transport Models

Approaches used to model the transport of a mobile solute such as nitrate through soil can be divided into two groups: deterministic models and stochastic models (Tables 1 and 2) (Addiscott and Wagenet, 1985). Predictive models are designed for estimating the effects of changing inputs or transfer rates on pool sizes, leaching losses, and related issues (Winteringham, 1984). Knowledge of two aspects is needed for a complete description of leaching: 1) the position of the chemical's peak concentration in the soil profile (i.e., solute center of mass); and 2) the shape of the leaching band (Smith et al., 1984).

Deterministic models develop a description of transport based on mass conservation and flux laws, and rely on differential equations to predict values of the water and solute variables as functions of position and time. In contrast, stochastic models describe the variables as random functions, which depend on the distribution of soil property values, to predict concentration averages and variances. These statistics are used to calculate the probability of having a given value appear at a given depth or time (Jury and Nielsen, 1989).

Deterministic models require detailed measurements of transport and rate coefficients for predicting nitrate movement through soil. The deterministic piston flow model provides only a rough estimate of nitrate movement, but can be applied using only minimal information about soil properties (Jury and Nielsen, 1989). However, the spatial variability of water and solute transport parameters in natural field soils has made it difficult to apply detailed deterministic models to field-scale solute transport. In 1985, Jury reviewed field-scale solute transport experiments and reported coefficients of variation of 60-200% for apparent solute velocity. Jury (1982) and Jury et al. (1986) proposed a stochastic, non-mechanistic solute transport model using a transfer function to represent solute transport and reactions implicitly.

Table 1. Review of leaching models (after Addiscott and Wagenet, 1985).

MECHANISTIC	FUNCTIONAL
DETERMINISTIC • presume system or process operates such that occurrence of given set of events leads to uniquely-defined outcome	
• define rates of change • usually based on rate parameters • driven by time • incorporate fundamental process mechanisms • based on convection-dispersion equation • serve primarily as research tools	• define changes • usually based on capacity parameters (less spatially variable than rates) • driven by rainfall, evaporation, irrigation • incorporate simplified treatments of solute and water flow • no claim to fundamentality • require less input data and computer expertise • input data obtainable independently of test data • more widely used as management guides
Analytical Solution • assume steady-state solute movement, steady-state one-dimensional water flow, homogeneous soil • general form, flexible incorporation of processes • widely usable if experiments simulated meet required boundary conditions • mainly restricted to controlled, homogenous, de-structured lab columns • main value is validating conceptual framework • Problems: 1. constraints of boundary conditions required rarely represent field conditions 2. some constants needed must be obtained by fitting model to test data 3. subject to problem of variability	Partially Analytical • assume piston flow, compute solute peak position, impose effects of dispersion and diffusion around peak • displacement calculated using water content at field capacity, not rates of movement • potential use as both research and management tools, but with limitations in each case • Problems: 1. cannot handle heterogeneous profiles or those which contain solute at depth at beginning of leaching period 2. do not address immobile water associated with intra-aggregate pores