PROJECT SUMMARY

Title: Fate of Representative Fluoroquinolone, Macrolide, Sulfonamide and Tetracycline Antibiotics in Subsurface Environments.
Project I.D.: WR03R008
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Background/Need:

The problem of antibiotics entering the environment from municipal and agricultural sources is well recognized and is a matter of growing concern. Several reports documenting the presence of antibiotics in groundwater, both in the U.S. and Europe, have been published within the last decade. Since soils are the recipients of various types of wastes and have the capability to serve as potential "sinks," a better understanding of processes controlling the interaction of antibiotics with soils is required. Quantification of the extent of sorption and elucidation of underlying mechanisms of interaction with soil constituents is especially important, because sorption determines the fraction of antibiotics that is available for transport to groundwater or is biologically active. Antibiotics possess molecular properties expected to favor their sorption to soil components. There is a paucity of information related to the fate and transformation of antibiotics in soil/water environments.

In a recent WI statewide survey of wastewater treatment plants funded by the GCC (Karthikeyan and Meyer, 2006), members of five antibiotic compound classes were detected in the following order of frequency: tetracyclines and trimethoprim > sulfonamides > macrolides > fluoroquinolones. These compounds were also detected in the first nationwide survey conducted by the USGS (Kolpin et al., 2002). In the WI survey, sulfamethoxazole (a sulfonamide) and tetracycline were also detected in groundwater monitoring wells adjacent to the treatment systems. Sorption of these antibiotics to soils can be expected to be controlled by the nature of their interactions with important soil components, such as clay minerals, hydrous metal oxides, and organic matter (both in dissolved and particle-bound forms).

Objectives:

The study objectives were to: (1) quantify the extent of sorption of selected antibiotics (one compound from each family of antibiotics detected in the WI survey: tetracyclines, sulfonamides, macrolides, fluoroquinolones) to humic substances (HS) associated with hydrous iron and aluminum oxides and smectitic clays; and (2) investigate antibiotic association with dissolved organic matter and how such association facilitates antibiotic transport under unsaturated flow conditions.

Methods:

A combination of macroscopic batch experiments and spectroscopic (using FTIR) analyses was employed to accurately quantify the extent of sorption as well as to elucidate underlying mechanisms. Radiolabeled versions of antibiotic compounds were used to facilitate monitoring the extent of parent compound sorption and transformation. Antibiotic-sorbent systems studied include: (a) tetracycline interaction with hydrous Al oxide (HAO), hydrous Fe oxide (HFO), humic acid (HA), and HAO-HA complexes; (b) ciprofloxacin (a fluoroquinolone) interaction with HAO and HFO; (c) sulfamethazine (a sulfonamide) interaction with montmorillonite, kaolinite, and humic acid-clay complexes; and (d) clarithromycin (a macrolide) complexation with HA. All experiments were conducted in the Departments of Biological Systems Engineering and Soil Science at the University of Wisconsin – Madison.

Results and Discussion:

Both tetracycline and ciprofloxacin formed strong inner-sphere complexes with HAO and HFO and the zwitterionic species appeared to be primarily involved in sorption interactions. The surface interaction of antibiotics with hydrous oxides occurred primarily on the edge Al/Fe atoms of HAO/HFO minerals, since these sites are not fully coordinated with the hydroxyl groups and are highly active. Ligand-promoted dissolution of hydrous oxides was observed during sorption and this process could conceivably increase the mobility of antibiotics. The tetracycline-promoted dissolution was more pronounced than ciprofloxacin, attributable to differences in the formation constants for the corresponding metal-antibiotic complexes.

Sulfonamide antimicrobial interaction with clay minerals was strongly pH-dependent, consistent with sorbate speciation and clay properties. Surface charge density appeared to influence sorption by determining adsorption domain size. Adsorption of uncharged sulfamethazine to montmorillonite was relatively insensitive to pH, ionic strength and type of exchangeable cation, while that to kaolinite was highly sensitive to ionic strength. Adsorption of cationic sulfamethazine to montmorillonite exceeded that of the neutral species by one to two orders of magnitude, but was unimportant for kaolinite at the pH values examined. Cation exchange appeared to contribute to sorption of cationic sulfonamide species to montmorillonite. Anionic sulfamethazine adsorption was negligible. The nature of the variable sulfonamide R group influenced the degree of adsorption of cationic and neutral species.

The interaction of tetracycline and clarithromycin with humic substances (HS) was influenced by both pH and ionic strength. Complexation of cationic/zwitterionic tetracycline species with deprotonated sites in HA (mainly carboxylic functional groups) appeared to be the major underlying sorption mechanism. Humic acid possessed a moderate sorption capacity for tetracycline with maximum sorption being less than 10% of tetracycline added (log K_{doc} values up to ~3.4). In contrast, clarithromycin sorption was strong (log K_{doc} values up to ~4.1). Clarithromycin was cationic over most of the pH range examined. Sorption of claithromycin sorption was strongly influenced by HA speciation. Aggregation of HA was observed to occur in the presence of tetracycline, which could help explain the hysteretic behavior observed in the sorption-desorption isotherms. This hysteretic behavior, indicative of irreversible sorption, could impact the bioavailability and degradation of humic-complexed tetracycline as well as enhance its mobility. Clarithromycin interaction with HA did not display sorption-desorption hysteresis.

Significant suppression of tetracycline sorption to HAO was observed in the presence of HA. Therefore, the presence of HS, both in dissolved and particle forms, could increase the subsurface mobility of tetracycline. It is expected that in organic-rich soil environments, tetracycline would have a high potential for off-site migration via both surface and subsurface pathways. In contrast, the sorption of sulfamethazine increased when clay minerals were coated with HA, and sorption-desorption hysteresis was observed.

Conclusions/Implications/Recommendations:

The study results indicate that propensity for antibiotics to migrate from the soil surface to groundwater depends on number of factors including their pH-dependent speciation, the ionic strength of the infiltrating water and the composition of the soil. Sulfonamide antimicrobials interact rather weakly with clay minerals and HS, suggesting that these compounds will be relatively mobile. In contrast, tetracycline and fluoroquinolone antibiotics interact strongly with HAO and HFO. Soils rich in these components (and relatively poor in HS) are expected to hinder the movement of these antibiotics through soil to groundwater. On the other hand, dissolved HS could increase the mobility of antibiotics by facilitating transport or by hindering their sorption to mineral surfaces (in the case of tetracyclines), thereby enabling inter-compartmental transfer of these compounds.

Related Publications:

Gao, J.; Pedersen, J.A. 2005. Adsorption of sulfonamide antimicrobial agents to clay minerals. *Environ. Sci. Technol. 39*, 9509 - 9516.

Gu, C.; Karthikeyan, K.G. 2005. Sorption of the antimicrobial ciprofloxacin to aluminum and iron hydrous oxides. *Environ. Sci. Technol. 39*, 9166-9173.

Gu, C.; Karthikeyan, K.G. 2005. Interaction of tetracycline with aluminum and iron hydrous oxides. *Environ. Sci. Technol. 39*, 2660-2667.

Gu, C.; K.G. Karthikeyan, J. A. Pedersen, Sibley, S.D. Complexation of the antibiotic tetracycline with humic acid. *Chemosphere* (*in review*).

Key Words: Ciprofloxacin, clarithromycin, sulfamethazine, tetracycline, hydrous aluminum oxide, hydrous iron oxide, montmorillonite, kaolinite, humic acid, humic-mineral complexes, FTIR spectrscopy
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