

GROUND-BASED MAGNETIC SURVEYS AS A NEW TECHNIQUE TO LOCATE SUBSURFACE DRAINAGE PIPES: A CASE STUDY

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ABSTRACT. *Identifying the existence and orientation of buried drainage systems is necessary to incorporate the impact of these features in solute transport and hydrologic models. This study was conducted to determine if a cesium magnetometer survey could identify clay tile locations. A cesium magnetometer survey with a sampling interval of 10 cm along the survey transect and 50-cm spaced transects was used at the Oregon State University Research Dairy in an attempt to map clay tile orientation and location. A shaded-relief plot of the magnetic data from a 100- × 100-m portion of the Dairy successfully identified clay tile in the western part of the study area, but was unable to identify clay tile in the eastern part of the study area. Probing and trenching confirmed the existence of clay tile in both portions of the site. This case study has shown that cesium magnetometer surveys can locate clay tile with a spatial accuracy (horizontally) of ±25 cm, and offers a new technique for non-invasive subsurface drainage pipe location. This study has also elucidated potential limitations in this method for identifying subsurface drainage pipe locations that may depend on soil type, management strategies, and soil magnetic properties.*

Keywords. *Cesium magnetometer, Clay tile, Subsurface drainage pipe.*

A clear understanding of the hydrology of an area is required before a determination of potential contaminant transport to surface and groundwater can be properly assessed. For that reason, the existence and orientation of subsurface drainage pipes must be considered when assessing water transport in areas that are, or have been used for, agriculture. Subsurface drainage pipes are typically installed to lower the water table, but they have also been found to reduce surface erosion and the corresponding transport of strongly sorbing pesticides by surface runoff (Kladivko et al., 2001). Moreover, this same system also may be responsible for significantly increasing nitrate and pesticide contamination to surface water bodies through percolation of solutes to drainage pipes (Bjorneberg et al., 1996; Bjorneberg et al., 1998; Cambardella et al., 1999; Chung et al., 2001; Gaynor et al., 2001; Jaynes et al., 2001a, 2001b; Munster et al., 1996). Clearly, determining the presence of subsurface pipes and their impact on flow properties must be incorporated in solute transport models.

It is not uncommon to have multiple generations of subsurface drainage pipe in agricultural fields. As pipes fill with sediment or for some other reason start to fail (Ford, 1993; Grass, 1969; Grass et al., 1973; MacKenzie, 1962) new pipes are installed usually without removing the old system. Even if old system locations were known, it is neither practical nor economic to remove them. It is important to note that even if an old drainage system has failed, rendering

it not useful for agricultural purposes, it may still affect the overall hydrology of the field. The location of all drainage installations in a field must be known before an accurate water quality transport model can be developed.

Various methods have been used with varying degrees of success for determining the existence and approximate location of subsurface drainage systems. Infrared aerial photography can be used to detect seasonal changes in soil moisture content or crop growth over tile lines (Scollar et al., 1990). Hand-held probes can be effective and inexpensive, but have two distinct disadvantages, they are time consuming to use and require many holes in close proximity, thus leaving behind long, straight macropores that can preferentially conduct contaminated water to drainage lines. Maps and other historical information are the most desirable method for obtaining data on drainage system installation, but a complete history for a site is rarely available or accurate. Ground-penetrating radar (GPR) can identify the depth to subsurface objects, but is not effective in soil with high clay content due to the extreme attenuation of the radar signal within the first few centimeters of soil (Conyers and Goodman, 1997). This latter method (Allred et al., 2004), however, has proven successful at locating agricultural drainage pipes in silty clay soils. Because subsurface drainage pipes are usually employed in poorly drained fields, which commonly contain high clay content, further studies need to be conducted to determine under what soil conditions GPR is effective in locating agricultural drainage pipes.

This article reports on initial testing of an additional method for determining the location of subsurface drainage pipes and other subsurface features of hydrologic importance. A cesium magnetometer uses optical pumping of cesium vapor to measure the magnitude of the earth's local magnetic field, which ranges from 30,000 nT in the equatorial regions to 60,000 nT near the poles. Readings are taken every tenth of a second with an accuracy of 0.1 nT. A cesium magnetometer in gradient mode consists of a pair of

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magnetometers separated by a distance (~0.5 m), oriented either horizontally or vertically to measure horizontal or vertical magnetic gradients. The two instruments are synchronized to take data simultaneously. Subtraction of the signal from the two instruments allows calculation of the gradient in the magnetic field. It is the gradient signal that shows the effect of near-surface objects. In computing the gradient, background fluctuations that equally affect both magnetometers are removed. The daily fluctuation of the sun, adjacent power lines, and distant automobile traffic all create background fluctuations that are removed by the gradient method.

In addition to the two magnetometers, the equipment consists of control cables, support staffs, a control unit, a battery pack with waist belt, and a shoulder harness (fig. 1). A single operator can carry this entire system. Rapid sampling speed of every tenth of a second allows data to be taken at normal walking speed along a survey transect, corresponding to a reading taken every 10 to 20 cm.

Local magnetic field variability can be generated by soil disturbance from deep trenching during pipe installation, by the pipes themselves or by elevated concentrations of iron within a clogged drainage pipe (Grass, 1969). Field tests have shown that pipe locations appear as a characterizable change in the magnetic signal as magnetic data is recorded along a horizontal transect. This phenomenon leads us to the hypothesis that a cesium magnetometer survey can identify clay tile locations at the Oregon State University Research Dairy with sufficient precision for inclusion in solute transport models. Furthermore, a cesium magnetometer has advantages over other methods because of its non-invasive-



Figure 1. Cesium magnetometer in vertical gradient mode and operator walking a typical survey transect.

ness, its effectiveness in high clay content environments, and its spatial resolution commensurate with that needed to locate subsurface drainage pipes. This article describes initial results of cesium magnetometer surveys used to map historical clay tile drain systems in a silty clay loam in the Willamette Valley, Oregon.

MATERIALS AND METHODS

The field site used for this study is a 0.1133-km² (28-acre) pasture that forms part of the Oregon State University Research Dairy. The pasture is clay-tile drained, with the most recent installation approximately 40 years ago. Oak Creek runs through the dairy and is managed for irrigation water and fish habitat. Maps showing the latest agricultural drainage system installation were not kept and there is no memory-record of prior installations.

The field was selected because excessive levels of *e. Coli* were found in Oak Creek and because dairy management uses the method of spraying liquid effluent on the clay-tiled fields as part of their nutrient and manure management strategy. Successful mapping of the clay tiles assisted in developing a drainage model for the area and was an essential component in determining if sprayed effluent was being preferentially transported to Oak Creek via the agricultural drainage system. A previous attempt to locate field clay-tile drains using a ground-penetrating radar survey with a 500-MHz antenna proved unsuccessful. Radar signals penetrated these soils no deeper than about 10 cm. Additional antennas were not available to the project, but decreasing the antenna frequency may aid in identification of subsurface drainage pipes using ground-penetrating radar. Allred et al. (2004) found GPR using a 250-MHz antenna to have an 81% average effectiveness at locating subsurface drainage systems at eleven test plots throughout Ohio. Chow and Rees (1989) had close to 100% success at locating clay tile and plastic drains in soils developed in morainal till, glaciofluvial, and glaciomarine deposits using GPR with a 500 MHz antenna. Clay content, water saturation, and iron content are some of the factors that influence the propagation of a radar wave through soils (Conyers and Goodman, 1997). Further studies of these properties may illuminate why GPR successfully imaged drainage pipes at the study sites in Ohio, but not at the Oregon State University Research Dairy. A cesium magnetometer was selected to map tile locations at the subject field site because of its likelihood for success, due to the possibility of it recording the clay tile's remanent magnetic signature, iron clogging in the tile, and the changes in soil iron distribution created by trenching. The ability of the cesium magnetometer to measure the magnetic signal of kiln fired pottery and ditches cut into soils is well documented in numerous articles and books (Clark, 1996; Gaffney and Gater, 2003; Scollar et al., 1990; Sharma, 1997).

Magnetic survey for this project used the vertical gradient configuration with a sensor spacing of 0.5 m. Vertical gradient mode was selected because the horizontal gradient can be calculated after data collection using the vertical gradient data, and the vertical gradient can be used to estimate depth to the source (Breiner, 1973). The Geometrics G-858 cesium magnetometer stores the magnitude of the earth's local magnetic field recorded by the bottom magnetometer, the top magnetometer, and the vertical gradient

between the two sensors and other survey information such as the time and horizontal position. The horizontal gradient can be calculated using the vertical gradient data by subtracting bottom magnetometer results or top magnetometer results for different horizontal positions. Estimating the depth to source using the vertical gradient is given by (Breiner, 1973):

$$z = \frac{-nT}{\frac{dT}{dz}} \quad (1)$$

where

- Z = depth to source (m)
- N = property of the anomaly type (e.g. $n = 3$ for a dipole and $n = 2$ for a monopole)
- T = total field anomaly (nT)
- dT/dz = the vertical gradient (nT/m)

SURVEY METHOD

A 100-meter-square study region was established inside of the 0.1133-km² (28-acre) pasture. The site was surveyed using standard survey equipment (a total station, prism, transit and stadia rod). The main survey grid was aligned with grid north, and the 100-meter-square study site was divided into twenty-five 20-meter squares or subunits (fig. 2). Grid and subunit corners were marked using PVC stakes. The low cost and non-magnetic properties of PVC make its use ideal for magnetic surveying.

For each subunit, fiberglass survey tapes were used to mark a baseline (E-W running line at the southern extent of the subunit) and a parallel control line (at the northern extent of the subunit). In the north-south direction, 21 blaze-orange 0.95-gauge plastic “weed-whacker” line served as transect lines and were stretched from the baseline to the parallel control line at 1-m intervals. Survey of the first subunit began in the southwest corner of the subunit (fig. 2), surveying continuously from south to north using a bi-directional survey method. When the northern end of the first transect was reached the gradiometer operator moved eastward 0.5 m and surveyed from north to south along transect two. Transects were separated by 0.5 m with one transect between each weed-whacker line. The position of the unmarked transects were estimated by looking at the marked transects. Marking only every other transect introduces a small amount

of error that is outweighed by the time saved when moving transect lines.

To assure continuity, after surveying half of the first subunit, and while the gradiometer operator continued surveying the subunit, a field crew moved the unneeded transect lines longitudinally to initiate marking of the second subunit. Upon completion of each subunit survey, the data file was closed and saved in the control unit. Each data file was programmed with the grid coordinates of the southwest corner of the respective subunit. For the 100-meter-square study site, upon reaching subunit #5, transects lines were laterally moved westward to the next series of subunits (see subunit #6 in fig. 2).

Using a 0.5-m transect spacing and an efficient crew, ten 20-m squares were surveyed per day. Under ideal conditions, establishing the survey grid and conducting the aforementioned magnetic survey could be accomplished in three days by an experienced three-person team. Conducting such a survey on the scale of a large agricultural field requires a sampling strategy other than the one used for this survey unless the time and money for extended surveying are justified. The results of this project suggest that pipe locations can be identified using a transect spacing of 1 m and acquiring data in a fashion similar to soil profile fence diagrams where a 20-m wide strip is surveyed, a 20-m wide strip is skipped, and the next 20-m wide strip is surveyed. Further studies are being conducted to identify optimum sampling strategies for various applications.

DATA PROCESSING

Geometrics Incorporated’s (www.geometrics.com, San Jose, Calif.) cesium magnetometer data acquisition control unit has a capacity limit of five files. Depending upon survey methods, these five files are not large enough to complete a typical survey. It is advantageous to have a portable computer available in the field to facilitate data transfer and to confirm data is valid early in the survey. A survey region 100 meters square, with survey transects spaced every 0.5 m, and data points recorded approximately every 0.1 m, generates approximately 250,000 data points per magnetometer. Data is transferred from the control unit to an analysis computer at the end of each survey day. Data files were converted from their native format to a comma separated variable format able to be imported into Golden Software’s Surfer mapping program (www.goldensurfer.com, Golden, Colo.). Each data file corresponding to a 20-m-square subunit will generate approximately a 1.0-MB file.

Surfer was used to merge the data files from each subunit. The merged data file was gridded using the Kriging method (Golden Software, 1999) with a grid spacing of $X = 0.075$ m and $Y = 0.075$ m. A shaded relief plot of the gridded data was produced using the Lommel-Seeliger Law method (Golden Software, 1999) with a central difference gradient. The Z-scale was set to 0.035 with the solar altitude at 25° and azimuth at 0° (fig. 3).

RESULTS AND DISCUSSION

Figure 3 is a shaded-relief plot of the gradient of the magnetic data for our 100-meter-square survey area after completion of data processing. Numerous subsurface features are evident. The largest magnetic anomaly (labeled A

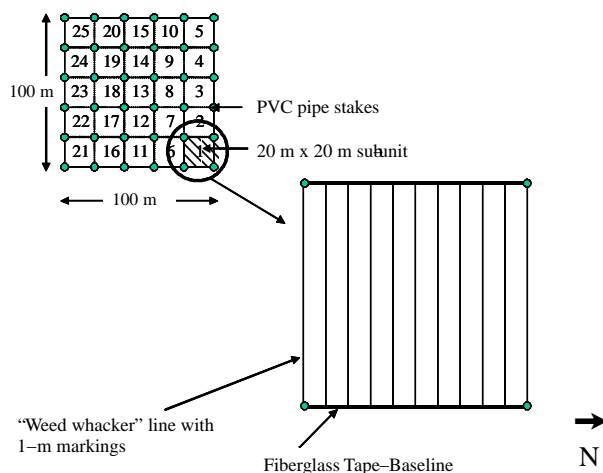


Figure 2. Diagram of survey method.

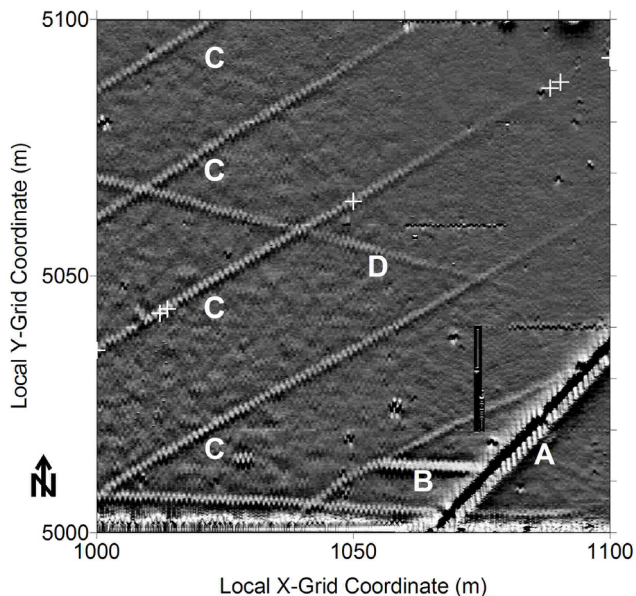


Figure 3. Plan-view shaded-relief plot of the gradient of the earth's local magnetic field. Letters represent features of interest and crosses mark known clay tile locations.

in fig. 3), running SW to NE in the southeastern portion of the survey region is consistent with a 30.48-cm diameter (12-in.) iron pipe 3 to 4 m beneath the surface. This anomaly is spatially located where a 1912 City of Corvallis planning map identifies a 12-in. water pipe. It is interesting to note that this pipe appears only on the 1912 map and is not marked on more recent maps.

The shaded-relief plot also presents other unknown and unexpected subsurface features. The east-west linear feature (labeled B in fig. 3) running along $Y = 5010$ m is a large, distinct magnetic anomaly whose source is unknown. Evenly spaced diagonal anomalies (labeled C in fig. 3) running from south-west to north-east are most likely associated with clay tile. An interview with the original tile installer (F. Price, personal communication, Oregon State University Research Dairy, 17 November 2001) places the tiles in the same orientation and spacing as shown by the data. Subsequently, tile probes and two soil pits dug the following summer confirmed the location of the tiles. A second diagonal anomaly (labeled D in fig. 3) normal to the first set may be related to an older tile installation that is not mentioned on any map or historical document, nor was this possibly older system verified in the field. Other smaller isolated magnetic anomalies appear throughout the survey region. The magnetic data also shows distinct differences in the overall "landscape" signature between the eastern and western portions of the study site. On the shaded-relief plot, the eastern portion of the plot looks "smoother" and the linear diagonal anomalies fade out. It is not clear why the magnetic data appears this way. Continuing investigations are exploring the role of soil type, soil management strategies, and variations in type, orientation, and depth of the buried object (Rogers, 2003).

Soil type can affect the ability of a cesium magnetometer survey to identify tile location due to varying concentrations of iron and iron-rich minerals within soil layers (Scollar et al., 1990). The act of trenching during tile installation may

cut through soil horizons. The resulting excavated soil may become mixed during excavation and backfilling of the trench, creating a soil with a new iron concentration compared to the unexcavated soils. If soil horizons have roughly the same iron concentration, the backfilled trench will have similar magnetic properties to the unexcavated soils and a magnetic survey will see little or no magnetic contrast between the backfilled trench and the rest of the soils. If one soil horizon has a large concentration of iron, then the soils in the backfilled trench will have a new, distinct iron concentration creating a magnetic contrast with the undisturbed soils. Soil management strategies can influence the landscape scale magnetic data by effecting magnetic properties of near surface soils through crop growth, fertilization, irrigation, plowing, and deep plowing. These management strategies affect the magnetic properties of soils by changing iron concentration through soil mixing, migration of iron within the soils, and enhancing the magnetic susceptibility of the soils (Scollar et al., 1990). The type, orientation, and depth of an object influences the success of a magnetic survey due to the strength of the object's magnetic field, the orientation of the object's magnetic field with respect to the earth's magnetic field, and the distance of the object from the magnetic sensor. An object with a small or large magnetic field in close proximity to the sensor will have a very strong signal, but due to the $1/r^n$ reduction in the magnitude of an object's magnetic field, only objects with large magnetic fields can be magnetically imaged when the object is deep in the soils. Quantification of the magnetic signal recorded by a magnetic sensor based on type, orientation, and depth of object has been studied for several objects (Breiner, 1973; Scollar et al., 1990), but a comprehensive look at these parameters for agricultural drainage pipes has not been accomplished.

As with any ground-based remote sensing method, the data is the product of the source and not a direct imaging of the source. Because different sources can produce the same image, it is therefore possible that a soil disturbance can produce a false positive. Interpretation of ground-based remote sensing data is the most challenging aspect of this research. When looking at the magnetic data from the Oregon State University Research Dairy the shape, orientation, length, and spacing of the linear anomalies all suggest that these magnetic anomalies are associated with an agricultural drainage system. This article presents a preliminary method for properly acquiring and interpreting magnetic data when attempting to map clay tiles. When likely tile locations are identified, tile probes can be employed to confirm the interpretation of the magnetic data in a more time efficient and less invasive way than using tile probes without the magnetic data.

Approximate locations of clay tiles were estimated to be at the center of the magnetic anomalies that are evident in the shaded-relief plot. Cross-sectional graphs of magnitude in the gradient field were examined at the approximate clay tile locations to identify the character of the variability that may be associated with clay tiles. Clay tile locations appear as local magnetic minimums of approximately 30 nT (fig. 4). The use of tile probes and field survey using a total station of actual clay tile locations showed that the spatial positions of local magnetic minimums were within ± 25 cm of actual tile locations.

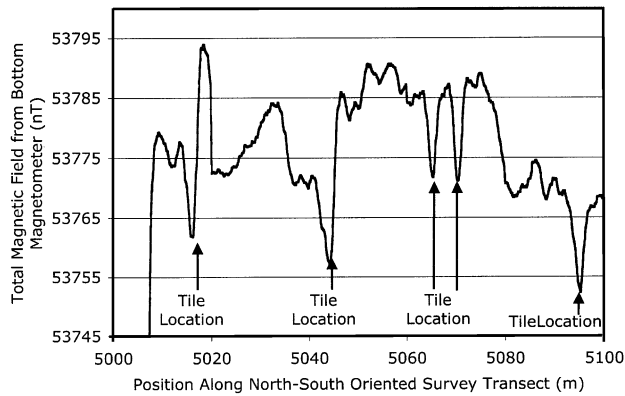


Figure 4. Profile plot of the earth's local magnetic field along one survey transect showing magnetic minimums spatially associated with tile locations.

Lab tests of a single clay tile section from the Oregon State University Dairy recorded a magnetic field strength of 1 to 2 nT at a distance of 1 m (the depth of the tile below ground surface at the study site). The strength of the magnetic anomalies spatially associated with the *in-situ* clay tile is approximately 30 nT. The significant difference between lab tests on the clay tile section and field data indicate that a source other than the clay tile is creating the 30-nT magnetic anomaly. Excavated clay tile sections contained no deposits or build up eliminating iron clogging as a source of the 30-nT anomaly. With these possible sources of the magnetic anomaly eliminated, the likely source is the soil disturbance during clay tile installation. The effect of soil disturbance during agricultural drainage pipe installation on the earth's local magnetic field is currently under study.

CONCLUSIONS

This case study has shown that magnetic gradiometer surveys can identify subsurface tile drain locations with a horizontal spatial accuracy of ± 25 cm when using a north-south oriented magnetic survey method with a transect spacing of 0.5 m. Conducting such a survey on the scale of a large agricultural field requires a sampling strategy other than the one used for this survey unless the time and money for extended surveying are justified. The results of this project suggest that pipe locations can be identified using a transect spacing of 1 m and acquiring data in a fashion similar to soil profile fence diagrams where a 20-m wide strip is surveyed, a 20-m wide strip is skipped, and the next 20-m wide strip is surveyed. The clay tile under study at the OSU Research Dairy is 22.86 cm (9 in.) in diameter and at an average depth of 1 m. A magnetometer survey is capable of locating these clay tiles to an accuracy that is on order with the size of the clay tile. This is clearly sufficient for most hydrologic studies. Further testing needs to be conducted to determine if this method can locate pipes smaller than 22 cm in diameter.

This case study has also shown limitations of magnetic gradiometers for identifying clay tile locations. The western portion of the study area exhibited magnetic anomalies spatially associated with clay tile, yet these anomalies disappeared in the eastern portion of the site. The clay tiles in question are of identical age, approximately at the same

depth, identical size, used for the same purpose, and visual inspection verified that they did not contain iron deposits. This strongly suggests that the lack of a magnetic signal associated with clay tile may be related to differences in soil magnetic properties due to different soil types and management strategies. Determining the soil conditions under which magnetic surveying can identify tile locations is very important and the subject of current study.

Three very important issues were brought to light by this case study. (1) Magnetic surveys were proven to be very useful for identifying historic subsurface features of hydrologic importance. This is of special importance in clay rich soil where ground-penetrating radar and other commonly used methods may be unusable. (2) This study established the range in signal strength that should be expected from a clay tile disturbance feature, thereby setting limits for usability of other magnetic surveying equipment. (3) Soil magnetic properties have a likely effect on magnetic signature at both a local and landscape scale. Soil properties should therefore be carefully considered in data analysis and experimental plan design. Work is under way to establish a key to soil properties that should be a precondition to selecting this remote sensing tool. Soil mineral content, local hydrology, and redomorphic processes may impact creation and longevity of magnetic anomalies resulting from anthropogenic disturbances. This methodology deserves attention, not only as a remote sensing tool, but also as a diagnostic tool for soil properties and processes.

REFERENCES

- Allred, B. J., N. R. Fausey, Jr. L. Peters, C. Chen, J. J. Daniels, and H. Young. 2004. Detection of buried agricultural drainage pipe with geophysical methods. *Applied Engineering in Agriculture* 20(3): 307-318.
- Bjorneberg, D. L., R. S. Kanwar, and S. W. Melvin. 1996. Seasonal changes in flow and nitrate-N loss from subsurface drains. *Transactions of the ASAE* 39(3): 961-967.
- Bjorneberg, D. L., D. L. Karlen, R. S. Kanwar, and C. A. Cambardella. 1998. Alternative N fertilizer management strategies effects on subsurface drain effluent and N uptake. *Applied Engineering in Agriculture* 14(5): 469-473.
- Breiner, S. 1973. *Applications Manual for Portable Magnetometers*. San Jose, Calif.: GeoMetrics.
- Cambardella, C. A., T. B. Moorman, D. B. Jaynes, J. L. Hatfield, T. B. Parkin, W. W. Simpkins, and D. L. Karlen. 1999. Water quality in Walnut Creek Watershed: nitrate-nitrogen in soils, subsurface drainage water, and shallow groundwater. *J. of Environmental Quality* 28(1): 25-34.
- Chow, T. L., and H. W. Rees. 1989. Identification of subsurface drain locations with ground-penetrating radar. *Canadian J. of Soil Science* 69(2): 223-234.
- Chung, S. W., P. W. Gassman, D. R. Huggins, and G. W. Randall. 2001. EPIC tile flow and nitrate loss predictions for three Minnesota cropping systems. *J. of Environmental Quality* 30(3): 822-830.
- Clark, A. 1996. *Seeing Beneath the Soil: Prospecting Methods in Archaeology*. London: B.T. Batsford.
- Conyers, Lawrence B., and D. Goodman. 1997. *Ground-Penetrating Radar: An Introduction for Archaeologists*. Walnut Creek, Calif.: AltaMira Press.
- Ford, H. W. 1993. Iron ochre and related sludge deposits in subsurface drain lines. In Circular 671. Gainesville, Fla.: University of Florida, Institute of Food and Agricultural Sciences.

- Gaffney, C., and J. Gater. 2003. *Revealing the Buried Past: Geophysics for Archaeologists*. Stroud, Gloucestershire, UK: Tempus Publishing Ltd.
- Gaynor, J. D., C. S. Tan, C. F. Drury, H. Y. F. Ng, T. W. Welacky, and I. J. Van Wesenbeeck. 2001. Tillage, intercrop, and controlled drainage-subirrigation influence atrazine, metribuzin, and metolachlor loss. *J. of Environmental Quality* 30(2): 561-572.
- Golden Software, Inc. 1999. *Surfer 7 User's Guide: Contouring and 3D Surface Mapping for Scientists and Engineers*. Golden, Colo.: Golden Software, Inc.
- Grass, L. B. 1969. Tile clogging by iron and manganese in Imperial Valley, California. *J. of Soil and Water Conservation* 24(4).
- Grass, L. B., A. J. Mackenzie, B. D. Meek, and W. F. Spencer. 1973. Manganese and iron solubility changes as a factor in tile drain clogging. I. Observations during flooding and drying. [Soil Chemistry]. *Soil Sci. Soc. Amer. Proc.* 37(1): 14-17.
- Jaynes, D. B., S. I. Ahmed, K. J. S. Kung, and R. S. Kanwar. 2001a. Temporal dynamics of preferential flow to a subsurface drain. *Soil Science Society of America J.* 65(5): 1368-1876.
- Jaynes, D. B., T. S. Colvin, D. L. Karlen, C. A. Cambardella, and D. W. Meek. 2001b. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. *J. of Environmental Quality* 30(4): 1305-1314.
- Kladivko, E. J., L. C. Brown, and J. L. Baker. 2001. Pesticide transport to subsurface tile drains in humid regions of North America. *Critical Reviews in Environmental Science and Technology* 31(1): 1-62.
- MacKenzie, A. J. 1962. Chemical treatment of mineral deposits in drain tile. *J. of Soil and Water Conservation* 7(3).
- Munster, C. L., R. W. Skaggs, and V. R. Pemmireddy. 1996. Effect of water table management on the fate of the pesticide aldicarb. *Transactions of the ASAE* 39(1): 55-66.
- Rogers, M. 2003. Effect of iron redistribution in soils on cesium magnetometer surveys at the Oregon State University research dairy. PhD thesis. Corvallis, Oreg.: Oregon State University.
- Scollar, I., A. Tabbagh, A. Hesse, I. Herzog, and R. E. Arvidson. 1990. *Archaeological Prospecting and Remote Sensing, Topics in Remote Sensing; 2*. New York: Cambridge University Press.
- Sharma, P. V. 1997. *Environmental and Engineering Geophysics*. New York: Cambridge University Press.