Visualizing relationships in interdisciplinary research with Geographic Information Systems: A case study utilizing food security research in Sahelian West Africa

Colin M. Minielly, Danish Rehman, Alexis Adams, Erika Bachmann, David Natcher, Derek Peak and Tom Yates*

Abstract

Achieving food security in the semi-arid region of West Africa remains challenging, primarily due to a combination of harsh climate and low soil fertility. The University of Saskatchewan, in partnership with many international organizations, has been researching solutions to increase the profitability of smallholder farmers in the region. This joint partnership aims at improving soil fertility for smallholder farming in Benin, Burkina Faso, Mali, and Niger. Data have been collected in eight different research sites, and include rainwater harvesting, crop yields, and soil samples. The data have a timeframe ranging from one year to many years. Prior to the University of Saskatchewan's commitment to the project, research data had only been utilized on a local scale, with relatively low success in sharing results and findings across national borders. With this project, collaboration occurred among multiple researchers from different countries and disciplines. A new technique used for collaboration was an interactive Geographic Information Systems (GIS) database. GIS has proven to be a powerful tool and platform for analysing and disseminating research data. This geospatial analysis laid the foundation for further research, resulting in a robust examination of soil and socioeconomic data from overseas.

Keywords: Geographic Information Systems (GIS), ArcGIS, West Africa, food security, microdosing, soil fertility

Food security is a pressing matter in the semi-arid region of West Africa. For the last three decades, this region has been affected by drought, famine, climate change, and poor availability of agricultural technologies. In some areas, such as Burkina Faso, food security has appeared to improve, but is not assured (West et al., 2014). Crop production in the West Africa region is predominantly limited by drought and poor soil fertility. Innovative technologies, including fertilizer microdosing and rainwater harvesting, have the potential to improve both

*College of Agriculture & Bioresources, University of Saskatchewan, Saskatoon, SK, Canada
Correspondence: colin.minielly@usask.ca

soil fertility and moisture, thereby increasing crop yield. Fertilizer microdosing involves the application of about half of the recommended fertilizer rate next to the point of sowing, within ten days of seeding (Abdoulaye and Sanders, 2005; Vanlauwe et al., 2010). Microdosing across the Sahel has improved yield by 1.5 to 2 times compared to unfertilized soil (Muehlig-Versen et al., 2003; Aune and Ousman, 2011). As well, microdosing improves nutrient-use efficiency more effectively than the recommended dose, lowering farmer investment and risk (Abdoulaye and Sanders, 2005; Aune and Ousman, 2011). Although microdosing, along with rainwater harvesting, has potential to increase yields up to 120%, only 5% of African farmers utilize these technologies (IDRC, 2014a). One comprehensive method to understand the impact of such innovative technologies on the food security of the semi-arid region of West Africa is to incorporate Geographic Information Systems (GIS) for spatial analysis of the ongoing research. GIS not only provides a comprehensive database of research results, but also allows users to draw spatial comparisons between results and create new knowledge. Such knowledge may guide development of best management practices for local growers, which may in turn support improvements to their food security.

The University of Saskatchewan is part of a multi-national research team working on issues surrounding Integrated Nutrient and Water Management (INuWaM) in West Africa. The four countries that are the focus of this project are Benin, Burkina Faso, Mali, and Niger, which are all located in the semi-arid belt of West Africa. The International Development Research Centre (IDRC) and the Department of Foreign Affairs, Trade and Development (DFATD), through the Canadian International Food Security Research Fund (CIFSRF), aim to improve the availability of soil nutrients and moisture to crops in the four countries involved (IDRC, 2014a). Other aspects of the project include evaluating socioeconomic dimensions of adoption and use of microdosing techniques.

The objective of this specific research project at the University of Saskatchewan is to develop an interactive GIS database consisting of multiple features of geospatial data and attribute information. This database was created in ArcGIS 10.2.2 from Environmental Systems Research Institute (ESRI) (Price, 2012). ArcGIS was used as a platform to input, analyse, and disseminate both new and pre-existing regional data. The regional data that have been input to this GIS database pertain to the climate, soil classification, geography, hydrology, and roads (infrastructure) of the region. Also, soil properties for each research site have been added, along with socioeconomic consideration for one of the research sites.

To illustrate the value of the GIS approach to this project, this paper provides three case studies: (1) Linking site properties to the available climate, soil, and landscape data to extend the results from a research plot level to a more regional scope; (2) Combining socioeconomic and soil fertility data to better understand an agrarian village in Benin; (3) Enhancing multidisciplinary collaborations and research through GIS.

Methodology

The ArcGIS database consisted of 20 layers based on data collected as part of a larger study. These included layers for political boundaries, infrastructure, and hydrology and climate information, obtained from public sources (Hijmans et al., 2005 a, 2005b). Layers for soil classes and slope characteristics were digitized by Bacon et al. (2014). Layers for soil analysis and socioeconomic research were obtained as part of the data collection process for the project. Included in the layer for soil analysis were results for soil samples from 805 locations, representing eight different research sites in Burkina Faso, Benin, and Niger. The socioeconomic layer included data for 73 household surveys completed in Koumagou B, Benin (Fig. 1). The eight sites represent different aspects of INuWaM project for food security, from water collection techniques to socioeconomic status. The soil samples were sent from their respective sites to the University of Saskatchewan's Soil Science Department for further analysis. All of the soil data were combined into a format that was compatible with ArcGIS and then input into the GIS database.

Soil chemical properties were analyzed by the University of Saskatchewan, using multiple techniques, to determine pH, electrical conductivity, organic carbon, total nitrogen (N), and total and available phosphorus (P). Soil pH and electrical conductivity were measured by glass electrodes, using a soil sample mixed with water in a 1:2 ratio. Organic carbon was determined by using a dry combustion method, using LECO-C632 carbon determinator (LECO© Corporation, 1987). Total N and P concentrations were measured using a single H_2SO_4-H_2O_2 digestion method (Thomas et al., 1967). The analyzed soil data were then manipulated and input into the GIS database using the geographic locations of each research site.

So that the research sites are adequately represented on the map, geographic data of the area was cquired from online sources, including topographic information and administrative boundaries. Soil

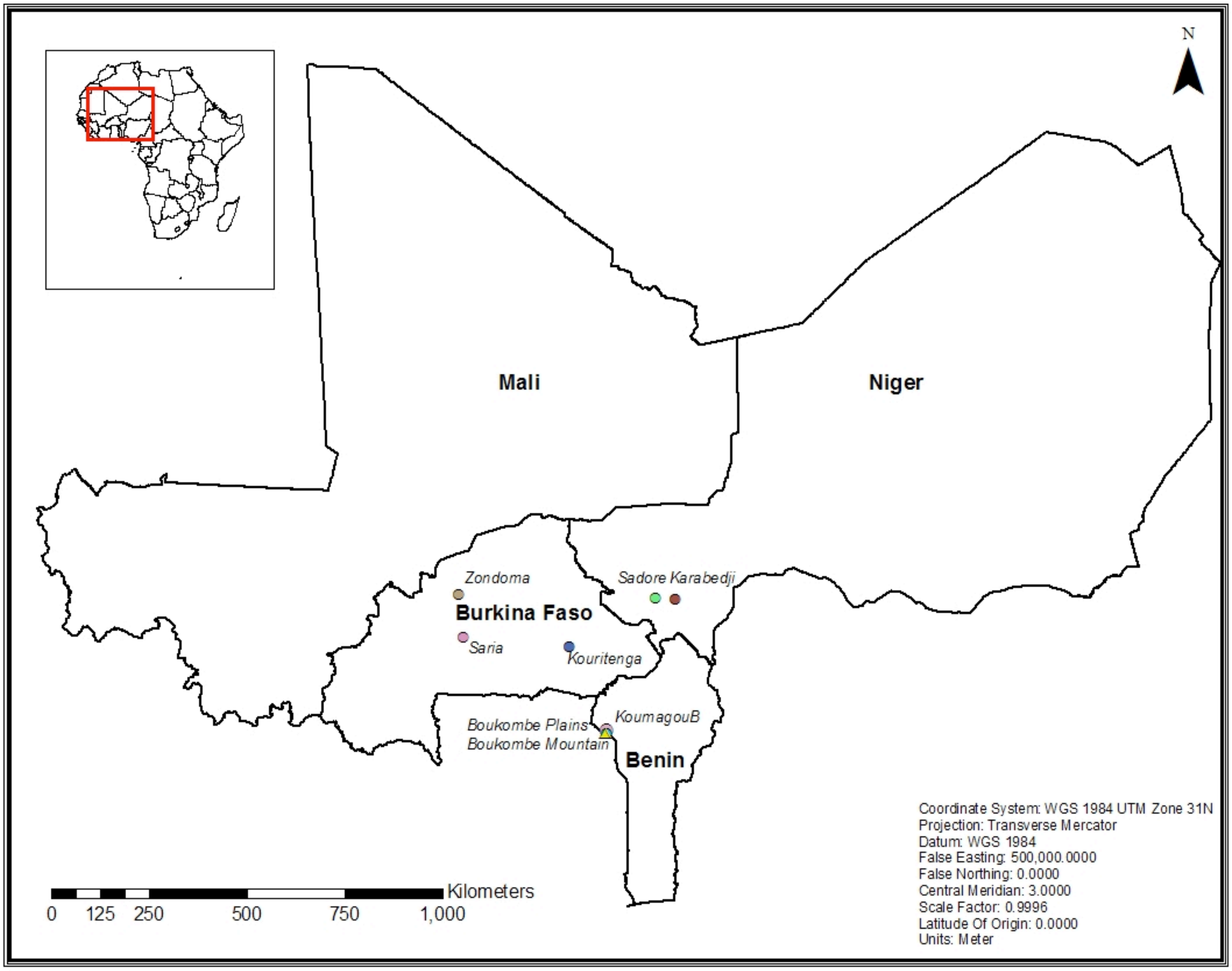

Figure 1: Location of INuWaM Research Sites, West Africa as displayed within ArcGIS.

classification data (containing major soil types) were obtained by georeferencing and digitizing maps from the European Commission's Soil Atlas of Africa, at a scale of 1:3000000. These soil maps were created as part of an objective set by the European Union, in partnership with the African Union (Jones et al., 2013). DIVA-GIS was the primary source for obtaining geographic and climatic data (Hijmans et al., 2005 a, 2005b). DIVA-GIS distributes data from multiple sources and in multiple formats, some requiring manipulation within ArcGIS software (Bacon et al., 2014). Administrative boundaries, annual precipitation, annual temperature, road networks, hydrology, and elevation were all obtained from DIVA-GIS on a per country basis (Hijmans et al., 2005 a, 2005b). Slope for the region was calculated using the slope tool, within ArcGIS, on the elevation layer. Since the files were per country, ArcGIS's variety of tools was used to merge the layers together and make a seamless transition between countries.

Analyzed soil data were manipulated from the original format into a Microsoft Excel spreadsheet, from which they were input into the GIS database according to the geographic locations of the research sites. These data represent soil properties important to crop production, sn uch as soil nitrogen, phosphorous, pH, electrical conductivity, and soil organic carbon. The socioeconomic data collected from 73 Koumagou B households were also included in the database, in the same format and with specific geographic locations, for the purpose of comparison to the soil sample analyses. The household socioeconomic surveys, which included a wide range of qualitative and quantitative data, were conducted as part of a Masters of Arts thesis project (Bachmann, 2014), and details are available in that document. As an objective for a similar project, Bacon et al. (2014) quantified a portion

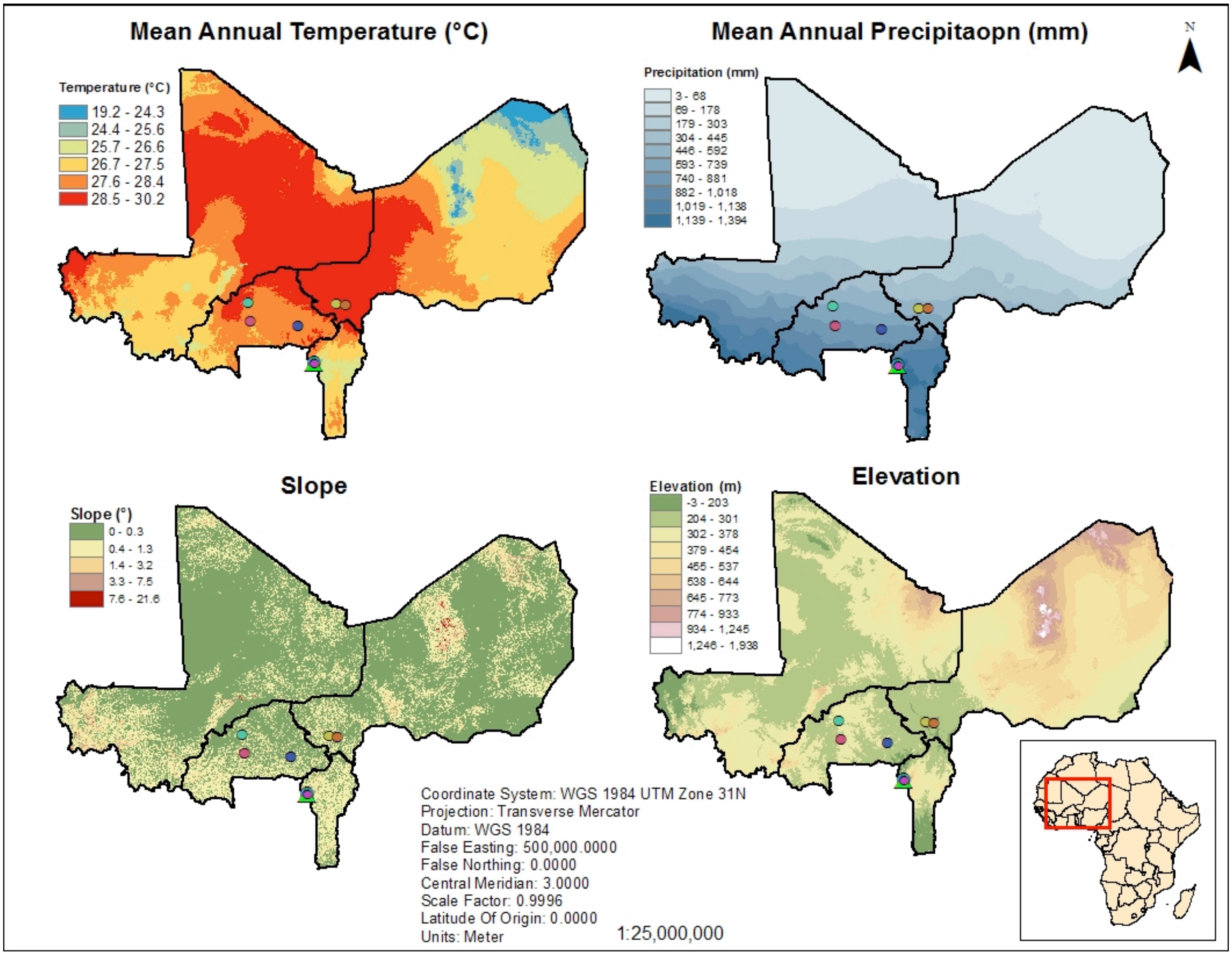

Figure 2: These maps show mean annual temperature, precipitation, elevation, and slope, respectively. Data obtained from DIVA-GIS (Hijmans et al., 2005 a,b).

of the survey results to isolate questions that pertained to the participants' socioeconomic status.

Results and Discussion

The University of Saskatchewan has been assisting the research work of its partner organizations by providing technical support, such as soil chemical and geospatial analyses and development of an interactive GIS database. The partnered researchers are tackling different aspects of the INuWaM project, such as the appropriate means of promoting microdosing techniques and the socioeconomic factors that influence food security in the region. The conception of the GIS database has contributed significantly to the soil fertility examination and socioeconomic considerations of the research sites.

Relation of Soil Sample Analysis to Climate, Precipitation, and Soil Type Maps, and Developing the Criterion to Expand the Data Regionally

The GIS database was created in a manner that allowed for significant amounts of data to be input. One type of data was crop yield, which was based on the microdosing research conducted on each site and acquired through collaboration with lead researchers. Seven of the eight sites had yield data for 2013; one had data from 1994 to 2013. The quantity and consistency of yield data collection varied across sites. The crop yield data were then combined with other soil chemical properties and completed at the University of Saskatchewan, resulting in soil fertility data for each research site. This joint consideration gave researchers at the University of Saskatchewan the opportunity to run statistical analysis on any preconceived hypotheses regarding the expected outcomes of the project.

Useful socioeconomic data were also collected from the village of Koumagou B. The questions from the survey served as the medium to calculate the socioeconomic status (SES) of each survey participant. Along with the socioeconomic data collected, a soil sample was taken from each site. The soil chemical data were used to create a soil quality index (SQI) for the project participants. The SES and SQI were then added to the ArcGIS database for further analysis.

Additional variables, including precipitation, temperature, elevation and slope, streams and rivers, road network, and soil types of the region were also input to the GIS database. Figures 2 and 3 are maps from ArcGIS showing mean annual temperature, precipitation, elevation, slope, and soil classification. These variables were primarily used to understand the distribution and differences among the research sites. Soil classification proved to be the key variable for the database to be comprehensive and robust (Fig. 1). The soil classification maps set the basis for the analyzed soil samples at the University of Saskatchewan. Hence, all the soil chemistry data were easily added, stored, and represented within the database, allowing for comparisons to be made between sites.

Socioeconomic surveys correlated with soil chemical properties and geo-referencing for Benin

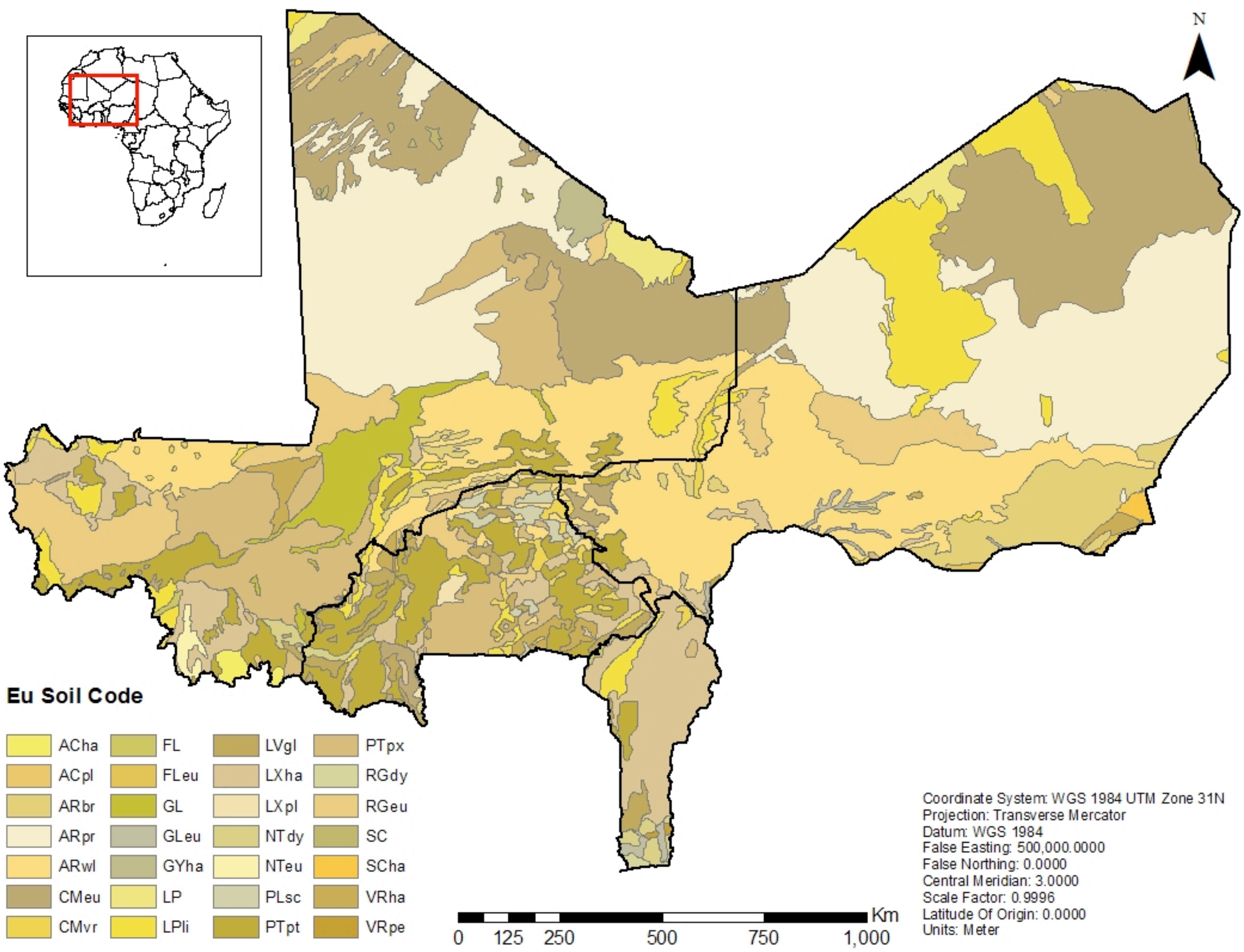

Figure 3: Soil Classification map. Data were created by Bacon et al. (2014) using the European Commission's Soil Atlas of Africa, at a scale of 1:3000000 (Jones et al., 2013).

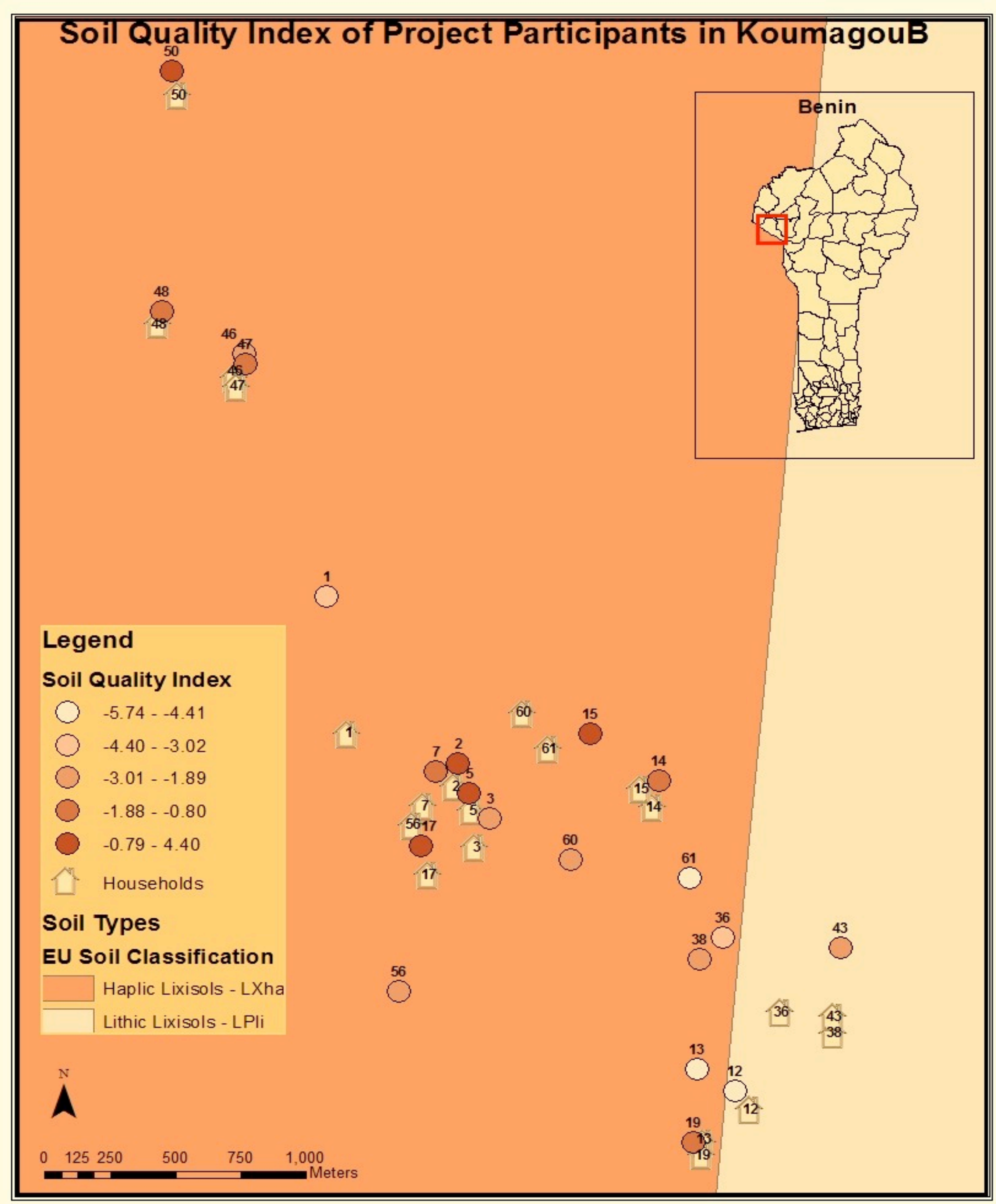

Figure 4: Relating the household, soil quality indices, and soil sample location for the village-scale study in Koumagou B, Boukoumbe, Benin.

The GIS database developers worked closely with a graduate student from the College of Agriculture at the University of Saskatchewan and lead researchers from West Africa, to analyze socioeconomic data and soil samples collected in the village of Koumagou B. One soil sample for each of the 73 households in the village was analyzed for chemical properties. All of the soil data for Koumagou B were input in the GIS database in the shape of the attribute tables. The spatial relationship among the different soil variables, for the respective soil sites, was used to create a single quantitative value that described the relative soil quality of all 73 households in the village, that is, soil quality index (SQI). The SQI provided a single measure of soil quality, in terms of the soil properties relevant to crop production, as described above. As a unit-less value, a high SQI indicated good quality soils, and a low SQI represented low quality soils. A general trend in West Africa is that the soils are heavily degraded and SQI is low. Using ArcGIS allowed calculation of both the distances between households in the survey of Koumagou B, and the distance that each survey participant traveled to their respective plots. ArcGIS had the ability to illustrate the spatial relationships among households. One hypothesis was that, as distance from household increases, soil quality declines (Tittonell et al., 2005; Zingore et al., 2007). ArcGIS validated this hypothesis by showing the distance to the plots and the SQI value, respectively. See Figure 4 for a representative map illustrating this relationship.

The SES data from the detailed household survey in Koumagou B were incorporated into the GIS database to develop a better understanding of the adoption of microdosing in West Africa at a micro-scale. The quantified survey data were input in the GIS database for a better visual representation of durable assets of the populace of the village. This visualization tool, combining soil quality and SES, was used to develop conceptual models for the Koumagou B village that were then tested using statistical tools such as regression and principal component analysis (PCA) (Bachmann 2014). Details of this analysis were outside the scope of our project.

ArcGIS as a tool for collaboration and enhancing participation of diverse groups in multi-disciplinary research

There has been a unique knowledge transfer in developing the GIS database. Initially, it was built under the supervision of Dr. Derek Peak, for an undergraduate group project in the Renewable Resource Management (RRM) program at the University of Saskatchewan. The group project was primarily focused on developing an interactive map consisting of multiple layers of data including soil, climate, topography, hydrology, and infrastructure (Bacon et al., 2014). It laid the foundation for the subsequent research developing the GIS database described in this study. This transition, from a simple undergraduate group study to an extensive research project, has made an immense contribution towards the utility of the geospatial aspects of the INuWaM study.

The transformation, from an undergraduate group study to an academic research project capable of generating output maps for a wide range of issues surrounding the INuWaM study, was a significant change in scope for the authors and for the knowledge-transfer component of the study. ArcGIS is an effective tool to show and formulate spatial relationships among a number of variables, which opened new prospects for the INuWaM study. For instance, a series of analyses has been performed, such as allocation of inferential area for further research on the microdosing technique, as well as statistical examination of the socioeconomic survey done for one of the research sites. This GIS database has enabled the researchers to identify trends in the data and propose theories to frame relationships among different variables.

The INuWaM study has covered four countries, involved many institutes, and had many prominent researchers representing it (IDRC, 2014b). As part of the research grant, researchers from INERA, University of Parakou, CIAT, and ICRAF, who were all responsible for different aspects of the project, came to the University of Saskatchewan to help assimilate data that had been collected over the project's duration. One useful method to assist in data analysis was to create a method of displaying and visualizing the project's various research sites. For this purpose, the ArcGIS database was extremely well suited and its improvements have led to increased collaboration among the lead researchers. The ArcGIS software has proved to be a powerful tool for collaboration and participation of all the partner organizations.

Conclusions

Improving food security in the semi-arid region of West Africa continues to be a major development research focus. Multiple international groups are conducting research, but this does not give local growers an increased sense of security. The authors set out to create a GIS database that would assimilate data from multiple research studies across the region. The GIS database allows for the extraction and comparison of data, which can be used to guide development of best management practices for the involved farmers. Data within the database include soil chemical analysis, socioeconomic surveys, and crop yields, which are key variables to crop development and, therefore, food security.

As a result of the GIS development, there was a knowledge transfer that occurred from the authors as they transitioned the database from an undergraduate group project to an instrument valuable in academic research. The knowledge transfer is expected to continue as many organizations utilize the output maps, and the GIS database has helped to formulate the relationship between socioeconomic considerations and soil quality parameters, enhancing the completed analyses within the study. The final benefit of the database is that it has been a key resource for the acquisition, dissemination, and strong collaboration among the multi-national research team.

References

Abdoulaye, T., and J.H. Sanders. 2005. Stages and determinants of fertilizer use in semiarid African agriculture: The Niger experience [Online]. Available at DOI: 10.1111/j.0169-5150.2005.00011.x. Agric. Econ. 32: 167-179.

Aune, J.B., and A. Ousman. 2011. Effect Of Seed Priming And Micro-Dosing Of Fertilizer On Sorghum And Pearl Millet In Western Sudan [Online]. Available at DOI:10.3390/agronomy4030436. Ex. Agric. 47(3): 419–430.

Bachmann, E. E. 2014. Making a little go a long way: The socio-economic factors influencing the adoption of fertilizer microdosing in northwest Benin. MA Thesis. Univ. of Saskatchewan, Saskatoon.

Bacon, K., L. Harding, C. Minielly, D. Rehman, B. Weir, and R. Willness. 2014. Using ArcGIS to Promote Innovative Solutions for Food Security in the Sahel Region of Africa. Univ. of Saskatchewan. Internal Report.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis. 2005a. Very high resolution interpolated climate surfaces for global land areas [Online]. Available at DOI: 10.1002/joc.1276. International Journal of Climatology 25: 1965-1978.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis 2005b. DIVA-GIS [Online]. Available at http://www.diva-gis.org/gdata (accessed October 21, 2015).

International Development Research Centre (IDRC). 2014a. Integrated Nutrient and Water Management for Sustainable Food Production in the Sahel [Online]. Available at http://idrc.ca/EN/Programs/Agriculture_and_the_Environment/Agriculture_and_Food_Security/Pages/ProjectDetails.aspx?ProjectNumber=106516 (accessed October 21, 2015).

International Development Research Centre (IDRC). 2014b. Better fertilizer use in the Sahel [Online]. Available at http://www.idrc.ca/EN/Documents/106516-Sahel.pdf (accessed October 21, 2015).

Jones, A., H. Breuning-Madsen, M. Brossard, A. Dampha, J. Deckers, O. Dewitte, T. Gallali, S. Hallett, R. Jones, M. Kilasara, P. Le Roux, E. Micheli, L. Montanarella, O. Spaargaren, L. Thiombiano, E. Van Ranst, M. Yemefack, and (eds.) Zougmoré R. 2013. SOIL ATLAS OF AFRICA. European Commission, Publications Office of the European Union, Luxembourg.

Muehlig-Versen, B., A. Buerkert, A. Bationo, and V. Roemheld. 2003. Phosphorus placement on acid arenosols of the West African Sahel [Online]. Available at DOI: http://dx.doi.org/10.1017/S0014479703001261.Expl. Agric. 39(3): 307–325.

Price, M. 2012. Mastering ArcGIS. 5th edition. McGraw-Hill, New York.

Thomas, R.L, R.W. Shread, and J.R Moyer. 1967. Comparison of conventional and automated procedures for N, P, and K analysis of plant material using a single digestion. Agronomy Journal. 59: 240-243.

Tittonell, P., B. Vanlauwe, P. a. Leffelaar, K.D. Shepherd, and K.E. Giller. 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya [Online]. Available at DOI:10.1016/j.agee.2005.04.003. Agric. Ecosyst. Environ. 110(3-4): 166–184.

West, C.T., A. Somé, and E.K. Nebié (2014) Famines are a thing of the past: food security trends in Northern Burkina Faso. Human Organization. 73(4): 340–350.

Vanlauwe, B., J. Kihara, P. Chivenge, P. Pypers, R. Coe, and J. Six. 2010. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management [Online]. Available at DOI 10.1007/s11104-010-0462-7. Plant Soil 339(1-2): 35–50.

Zingore, S., H.K. Murwira, R.J. Delve, and K.E. Giller. 2007. Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. [Online]. Available at DOI:10.1016/j.fcr.2006.12.006. F. Crop. Res. 101(3): 296–305.