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Monitoring Wildlife Interactions with Their Environment: an Interdisciplinary Approach

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Research Article

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ABSTRACT

Objective: In a rapidly changing world, wildlife ecologists strive to correctly model and predict complex relationships between animals and their environment, which facilitates management decisions impacting public policy to conserve and protect delicate ecosystems. Recent advances in monitoring systems span scientific domains, including animal and weather monitoring devices and landscape classification mapping techniques. The current challenge is how to combine and use detailed output from various sources to address questions spanning multiple disciplines.

Methods: WolfScout wildlife and weather tracking system is a software tool capable of filling this niche. WolfScout automates the integration of the latest technological advances in wildlife GPS collars, weather stations, drought conditions, and severe weather reports, and animal demographic information. The database stores a variety of classified landscape maps including natural and manmade features. Additionally, WolfScout's spatial database management system allows users to calculate distances between animals' location and landscape characteristics, which are linked to the best approximation of environmental conditions at the animal's location during the interaction.

Results: The WolfScout system is an exemplary utility that provides researchers with an interdisciplinary approach to monitor wildlife interactions with their environment. To standardize information used in research projects, high quality data from multiple scientific fields is integrated and formatted for direct analysis. The animal, weather, and spatial calculations with landscape metadata can be extracted in various combinations through the web-interface dependent on the proposed hypotheses and desired mathematical models. Successful deployment at Fort Bragg Military Reserve resulted in management implications for wildlife-longleaf pine ecosystems.

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Conclusion: The WolfScout wildlife and weather tracking system promotes interoperability between data sources, software applications, and research projects, which facilitates our ability to tackle and model complex questions affecting wildlife interactions with their environment. The development of this novel data management tool is a solid step towards the future direction of interdisciplinary science.

INTRODUCTION

Understanding the spatiotemporal movements of wildlife in a given area is essential for unraveling the complexities of inter- and intra-species interactions, resource use, and disease transmission. Empirical information related to the interplay of these ecological components is often lacking or difficult to obtain. However, with current technology, we can monitor animal interactions and gain insight into environmental forces driving animal movements[1]. Climate and weather are important drivers for how animals use their environment but this relationship is poorly understood[2-4]. With current concerns about the effects of shifting climatic parameters and an increase in extreme weather events, the importance of understanding and modeling how environmental factors affect animal behavior is paramount[5-8]. To address these complex questions, research must combine large amounts of data from multiple scientific disciplines over space and time.

Current trends in animal tracking research are taking advantage of the cutting-edge technology presented by global positioning system (GPS) networks [9], which have the ability to produce highly accurate point locations at user-set intervals. Advancements in wildlife GPS collars have enabled near real-time remote data collection via Global System for Mobile Communications (GSM) cellular modems located within the collar device. Many new GPS collars include a variety of sensors (e.g., mortality, temperature, 2-axis activity, and hibernation sensors) in addition to the traditional very high-frequency (VHF) radio-tracking beacon, which have enabled researchers to precisely address a wider array of ecological questions[10,11].

The flexibility arising in data collection from these GPS collars has greatly increased the amount of information requiring post-processing and analysis. For example, with VHF collars, a researcher manually collects locations from their study animals, depending on the number of animals and available manpower, either once a day or once a week and often for only a season at a time[12]. With GPS collars, the receivers can be scheduled to collect location data at very frequent intervals for a relatively long period of time, dependent only on battery power and method of data storage. For example, GPS collars can be set to collect points and sensor data every 20 minutes for over a year. The enormous increase in the amount of information being collected challenges current methods of data processing and analysis.

Traditionally, researchers have manually collected, error checked, formatted, and entered data before analysis could even begin. With the amount of information available and the complexity of questions being addressed, the traditional approach is overwhelming, time-consuming, and error prone. Additionally, current software programs are geared towards handling small, discrete packets of data acquired from VHF collars, not the streaming, continuous data collected by GPS systems. The need for new methods of data management for wildlife monitoring is apparent[13].

The next challenge is integrating the large data sets of animal movements from multiple sources (e.g., GPS collars, meteorological databases including weather stations, topographical maps, remote sensing data, spreadsheet data) that allow analyses of animal movement and interactions with the environment in a systematic, standardized manner. Due to the massive amount of data being collected in near-real time at high frequencies across multiple disciplines, data integration can be extremely overwhelming to a researcher trying to combine even one or two sources of information[14,15]. Also, these data need to be processed and stored in a way that facilitates importation into multiple software analysis programs and made available to a variety of users with different goals. With interoperability of data and software applications, complex questions that span multiple fields of science can be addressed.

We believe a systematic approach with a database management system (DBMS) core is the best way to pursue this type of interdisciplinary research. A well-designed DBMS, such as PostgreSQL/PostGIS, consists of a long-term, high volume storage device that can handle real-time, multi-user data retrieval with spatial analysis capabilities. Subsequent infrastructure (software development) can provide data integration from multiple sources, automated data processing, spatial analysis, and output directly exportable in the correct format into a wide range of applications. Common standards for interoperability in data processing, data exchange, and software use are possible with this type of approach[13,16]. Ultimately, a DBMS should allow for more complex questions to be addressed in a rapid, reliable, and repeatable manner to aid in management decisions based on scientific research.

Spatiotemporal data repositories are recently being used to handle near-real time data retrieval and storage but only a few are programed to integrate different types of scientific data or automate data processing such as error checking[17]. Unfortunately, systems that do collect multiple types of data are often limited in scope, accessibility or customization. Currently, there are a few systems that have been created to integrate animal tracking data along with additional information to address specific research questions. Satellite Tracking and Analysis Tool (STAT) is an example of a successful database-powered system developed for inte-

grating marine animal movements with environmental information (e.g., remote sensing imagery) and anthropogenic disturbances such as fishery distribution[18]. Integrated System for Analysis and Management of Ungulate Data was designed to handle GPS data of 28 roe deer (*Capreolus capreolus*) with automated home range analysis[16]. More recently, EUropean ROe DEER Information System (EURODEER) is a login-restricted, web-based spatial database that stores movement data on roe deer integrated with environmental and socioeconomic datasets (www.eurodeer.org). Similarly, Movebank is a global online database that contains a place for researchers to upload any animal tracking data for storage and visualization with access to satellite remote sensing data when and where available[19]. Each of the above databases attempts to create a platform where information can be archived and easily accessible to multiple researchers to answer different types of questions.

To address questions of how current environmental conditions affect animal movements and interactions with their surroundings, we propose a prototype data integration system called WolfScout **(Figure 1).** WolfScout automates the integration of the latest technological advances in wildlife GPS collars with weather stations, drought conditions, and severe weather reports along with animal demographic information. With a spatial DBMS at its core, WolfScout provides users with the ability to calculate distances between animals and either classified landscape data or other animals. With this software tool, research can take a new interdisciplinary approach to monitoring wildlife interactions with their environment.

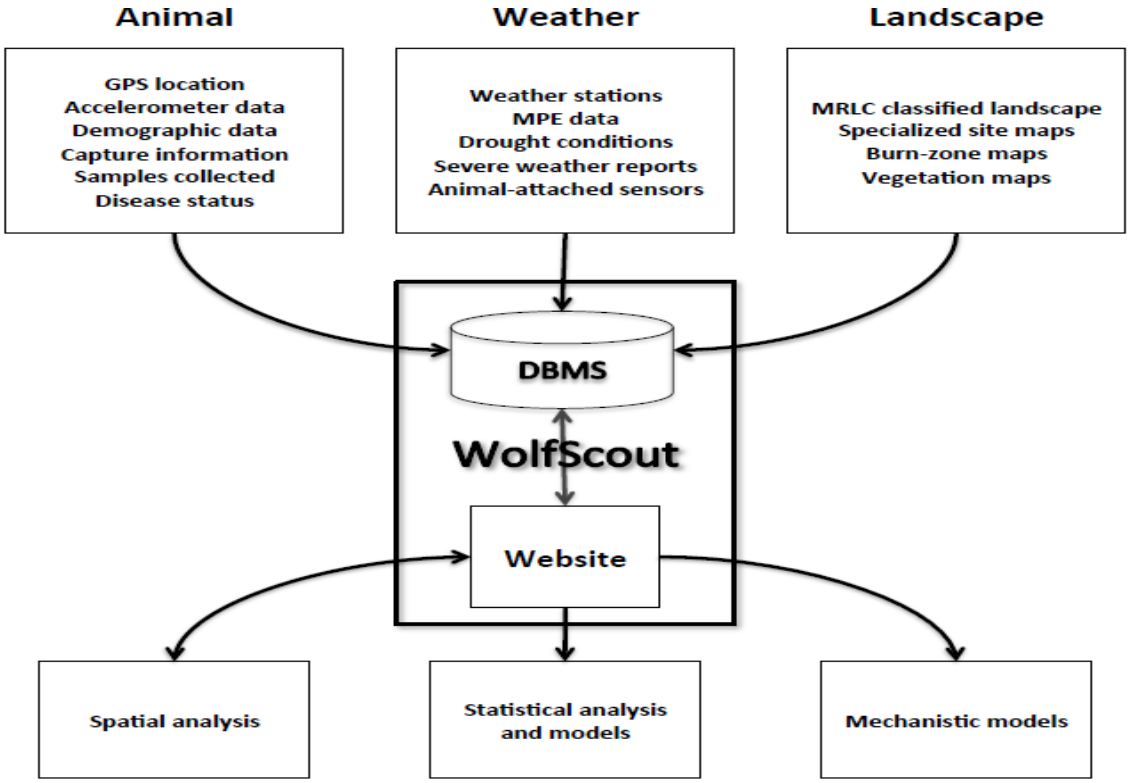

Figure 1. WolfScout wildlife and weather tracking system schema. Animal, weather and landscape data are integrated into the DBMS, which, in addition to spatial analysis tools, is made available to the client through a secure website. Data output can be directly imported into multiple software applications for further visualization and analysis.

SPATIOTEMPORTAL DATA MANAGEMENT SYSTEM

WolfScout wildlife and weather data integration system is specifically designed to facilitate interdisciplinary research combining the most current information and technological advances in each of the pertinent scientific fields. This system is one of the first solutions towards interoperability in data processing, data exchange, and software use among researchers. WolfScout automates collection of streaming data, integration, and manipulation of large amounts of data from "raw" data sources across scientific disciplines, such as wildlife biology, meteorology, and geographic information science. Accessing the data through a secure website, researchers can export selected data from the system directly into statistical, mechanistic modeling, or geospatial analysis programs to address questions of concern. By standardizing and speeding up data query, collection, formatting, and error checking, this method shortens the days and hours standard for current practice to minutes and seconds. Also, WolfScout can automate time-consuming tasks, such as calculating interactions between two moving targets or a moving and a stationary target, giving the user near instantaneous results that can address questions regarding animal interactions with their environment.

Framework

The WolfScout wildlife and weather data integration system contains basic functions necessary for data collection, error checking and storage of location and weather data along with calculating interactions between moving and/or stationary targets and a user interface **(Figure 2).** The system prototype currently runs on a Linux server, but it is capable of running on a wide variety

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of platforms, including Windows and MacOS X. WolfScout includes only open-source technologies and contains a spatial DBMS, PostgreSQL and PostGIS, as the foundation providing an ACID (Atomicity, Consistency, Isolation, Durability) compliant geospatial data storage solution with spatial and temporal data manipulation capabilities. A PHP (PHP: Hypertext Preprocessor) web application bridges the gap from the database to the web, while Django-powered Python code processes GPS input files and weather information. This design allows for reliable, fast access to the database and authentication support to secure data access. All WolfScout requests are made through a web interface providing remote access to the database for multiple users. By standardizing the process, WolfScout data is easily accessible to other utilities and clients. Currently, downloadable data is formatted for direct importation into commonly used software programs (e.g., Excel, ArcGIS, R, and Matlab) so that further modeling can be done using empirical data from the WolfScout system.

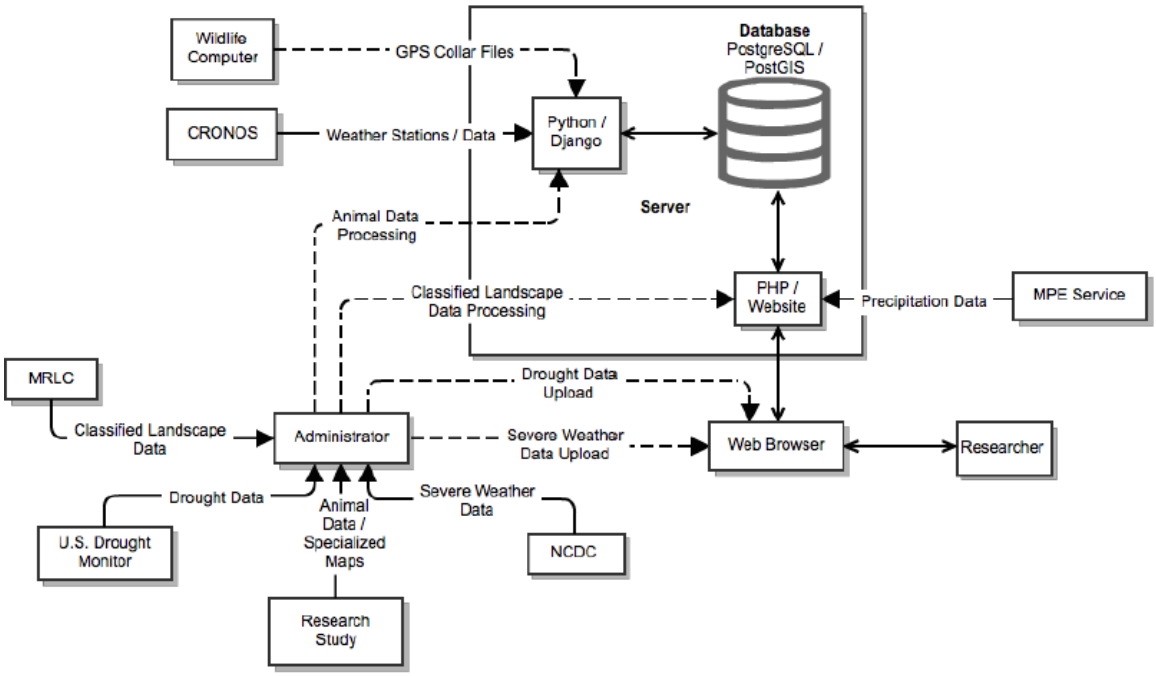

Figure 2. WolfScout high-level diagram. A graphical representation of the WolfScout software architecture system used to integrate high quality data from a variety of scientific disciplines. This software provides the researcher with a remote way to model wildlife interactions with their environment.

Data Access

WolfScout's vision is to address questions regarding how environmental conditions affect animal interactions within a given landscape. To accomplish this task, the database spatially and temporally links wildlife GPS collars to weather data, drought conditions, severe weather reports, and animal demographic information. A password protected, web-based graphical user interface provides researchers access to the system from anywhere in the world.

The website contains four major sections: Dashboard, Export All Data, Export Study, and Export Spatial Interaction. The Dashboard consists of references and instructions to help users navigate through the website. The Export All Data section allows researchers to access all of the data fields available in the database and provides the researcher with a place to access all stored data from their study. The Export Study section contains a subset of the database fields most likely to be used in analysis. For example, the animal demographic information available in this section contains only species, sex, age class, study location, collar number, and common name whereas the Export All Data section may contain animal disease status and body measurements. The Export Spatial Interaction section is a specialized feature that calculates distances from the animals in the database to either stored classified landscape data or user-uploaded Environmental Systems Research Institute (ESRI) shapefiles (here forth, shapefile).

Every feature in the website is designed to allow the user to choose what data is downloaded and whether it is in a shapefile or comma separated value (CSV) format. First, the user specifies the dates and time of day for data retrieval and then selects the animals, either by name, species, sex, age class or location. Second, various filters (Animal Demographics, Collar Data, Station Weather, Severe Weather, and Other Weather) contain the spatially and temporally linked database information that can be chosen for downloading. By giving the user flexibility in what data is downloaded and in what format, different questions that relate environmental conditions to animal location can be addressed.

Datasets and Automated Processing

The WolfScout wildlife and weather tracking system combines datasets from a variety of sources to provide the user with a range of environmental conditions whose impact on animal location can be evaluated either together or separately. Each of these datasets is from a different source and requires different methods of data collection and processing for integration into the data-

base. Post-processing of the data within WolfScout provides automated standardization of the data used in research projects. The major classes of information present in the database are animals, weather, and landscape.

The animal data can be broken down into two sources: manually and GPS collar collected. Currently, WolfScout collects animal data from coyotes (*Canis latrans*) and white-tailed deer (*Odocoileus virginianus*) equipped with Lotek WildCell GPS collars (Lotek Wireless Inc., Newmarket, Ontario, Canada). The researchers provide a spreadsheet containing all of the manually collected data to be stored in the database on each animal, which requires specific demographic information (sex, age, species) and start/end dates the animal was GPS collared. Also, data may include research specific measurements, samples, capture information, and disease status. Each animal is temporally-linked to a collar number. The collar data are sent from animals in discrete packets via cell tower paths to a remote computer where the system automates the retrieval. The information uploaded to WolfScout from the collars includes GPS coordinates, activity monitor and temperature sensor readings. The collar data, which is also stored on the collar itself, may be manually uploaded to the system in case of transmission failure in any step from animal collar to database.

The animal location data are spatially and temporally linked to weather data. WolfScout collects weather data from a variety of sources, each requiring a different method of integration. There are four different types of meteorological data: weather stations, multi-sensor precipitation estimates (MPE), drought conditions, and severe weather reports. Weather station data is collected from Automated Surface Observing Systems (ASOS) and Automated Weather Observing Systems (AWOS) networks through the North Carolina Climate Retrieval and Observations Network of the Southeast Database[20] application programming interface (API). Once the database receives a GPS point from a collar, the closest weather station to that location is automatically calculated. A web API retrieves and integrates the weather station information into the database based on the GPS point day, hour and minute where available, while another API collects MPE data from the State Climate Office of North Carolina[21]. In this case, the API accepts latitude and longitude coordinates derived directly from the collar data and returns radar-derived rainfall estimates for locations between weather stations at a resolution of 4.7 km. Drought conditions are collected from the U.S. Drought Monitor archive (2012) and uploaded to the database through the website's graphical interface[22]. Each GPS point is matched to the corresponding drought condition based on location, date, and time. Severe weather reports are generated from the National Oceanic and Atmospheric Administration's National Climatic Data Center (NCDC) Storm Events Database (2012), which is currently manually downloaded from the NCDC database and study-specific locations are extracted[23]. Newly created files are then uploaded into WolfScout where they are processed and linked to the animal location by county and can be queried on the website either by the hour or day of the GPS point.

Classified landscape data covering the research study location is preloaded in the system. Maps, manually uploaded to the server, are a compilation of resources from the study site land managers (i.e., Fort Bragg Military Installation, North Carolina) and from the Multi-Resolution Land Characteristics Consortium (MRLC) [24]. A multitude of land cover classes are available on the website, including water, forest stands, prescribed burn zones, agricultural land, vegetation, wildlife preserve areas, barren areas, and developed land. As GPS points are added to the database, the system automates and saves distance calculations from each animal location to the closest object in each classified landscape type, which allows for rapid retrieval of a user-specified subset of data through the website interface. WolfScout allows users to upload their own shapefile and will calculate and output the distance from every GPS point in the subset of animals chosen to the closest object in the shapefile. The shapefile can contain points (e.g. from other animals), lines/polylines (e.g. transect data), or polygons (e.g. study plots) allowing for maximum flexibility in this function.

All of the information present in the database is subject to standardized quality assurance testing. Each Wide Area Augmentation System (WAAS)-enabled GPS point is internally checked for errors such as impossible dates, repeated entries, and missing latitude/longitude information. Based on research standards, only GPS points with a dilution of precision of ten or less are made available in the Export Study Tab. All weather data sources were chosen due to their own stringent quality assurance standards. A formal accuracy assessment was performed on the MRLC 2006 classified landscape data present in the database. The classified landscape data provided by the study site is under governmental mandate and most are updated yearly. Additionally, the database tables have internal error checking that ensures the data is properly entered into the database. WolfScout provides a standardized dataset that is subject to the highest quality standards available for each discipline.

Applications

The WolfScout wildlife and weather tracking system is an exemplary utility that provides researchers with an interdisciplinary approach to monitor wildlife interactions with their environment. To standardize information used in research projects, high quality data from multiple scientific fields is integrated and formatted for direct analysis. The animal, weather, and landscape data can be extracted in various combinations through the web-interface dependent on the proposed hypotheses and desired models.

Statistical models can be developed directly from downloadable data. From the Animal Study Tab, a researcher can examine how environmental conditions correlate with animal location, which may include weather variables (e.g., temperature, humidity, and precipitation) and extreme weather events (e.g., thunderstorms, tornados, flash floods, hail, drought or wildfires). From the Spatial Interaction Tab, data can be used to study how animals use the natural resources in their study area, including variables

(e.g., water, forest cover and vegetation) or other features of interest (e.g., man-made burn zones or developed land). With the ability to overlay the weather data with the spatial data, more complex questions regarding how specific environmental conditions affect the animal's use of the landscape can be addressed. For example, the WolfScout system has been successfully used to integrate multiple databases to evaluate the influence of weather variables on both coyote and deer distances to lowland areas on the Fort Bragg Military Reserve[17]. Additionally, the Spatial Interaction Tab can be used to investigate weather variables that may correlate with distances between animals (i.e., animal-to-animal interactions). All of the data are downloadable in a CSV file formatted for direct use by statistical analysis programs, such as R, MatLab and SAS.

Geographic analysis can be performed on any subset of the available GPS data from any tab, which may include home range calculations, buffer zone analysis, or simple data visualization. With the option of shapefile export, the data are formatted for direct importation into ESRI ArcGIS, arguably the most commonly used software program for geographic information science (GIS).

WolfScout is a remote storage solution for any type of animal related data, including capture information and disease status. With the option to download any of the stored data together, the additional information may be used for general study statistics on captured animals and a variety of other mathematic models. The long-term storage feature promotes data exchange and cooperation between researchers by enabling secure access to all study information from any computer that is connected to the Internet. Ultimately, the stored data is available to address a multitude of questions beyond the original research purpose.

WolfScout can be programmed to extract data from almost any utility, or provide access to any server, all from almost any client. Thus, Wolfscout could extend the use of its DBMS to automate interaction calculations for improving any entity that desires to know where moving targets (i.e., animals or people) are located in relation to each other or landmarks of interest. The landmarks of interest may include wildlife protected areas, wildlife centers and hunting areas looking to make informed management decisions or forensic and diagnostic laboratories trying to identify epicenters of concern. Additionally, government mandated environmental assessments related to land use, development and air space use would benefit greatly by WolfScout's integrated approach for managing large sets of data to determine adverse impacts on wildlife.

Potential Limitations

Potential limitations to the WolfScout system would revolve around changes that may occur in the future without having technical support for the system. Currently, the system's APIs are designed for data collection through specific web servers. If access to these web servers were to change in the future or if new technological advances affect the way data is stored or formatted, the current WolfScout implementation would need to be reconfigured to fit the new requirements. However, the fundamental basis of the WolfScout weather and wildlife tracking integration system, using a DBMS at its core, will always be a strong, flexible platform that can be tailored or updated for any type of data application with proper technical guidance.

DISCUSSION

A breadth of detailed information is collected daily about biotic and abiotic elements in diverse ecosystems. Understanding the relationship between these elements within any given ecosystem is paramount for wildlife research to advance[25]. We have outlined a tool that can be used to progress from simple descriptive models of animal behavior to mechanistic models that incorporate biological significance to the relationships observed. This change requires a focus towards interdisciplinary research to provide an infrastructure for modeling these complex systems[1,26].

The capability to integrate different types of data from different sources in a standardized manner is essential for efficiently processing the enormous amounts of information available to address these higher-level questions. With large technological advances in animal monitoring devices, massive amounts of location data are now being combined with animal-attached sensors to provide a researcher with an overwhelming amount of data that needs to be stored, processed, and error checked[13]. Furthermore, questions concerning the impact of the environment, including climate change and anthropogenic factors, on movements, resource selections, and disease cycles of these animals introduces additional complexity and data that needs to be processed together[1,2]. WolfScout provides an elegant way to standardize the management and integration of all of this data from cutting-edge technologies in different fields of study to provide the user with the unique ability to quickly calculate important interaction parameters between objects and easily export this empirical data for analysis.

The WolfScout wildlife and weather tracking system promotes interoperability between data sources, software programs, research projects, people and organizations, which facilitates our ability to tackle and model complex questions affecting wildlife interactions with their environment. The ultimate goal is to facilitate management decisions impacting public policy based on rigorous research findings linked across multiple disciplines. The development of this novel data management system to automate collection, integration, and processing of environmental data from many different sources relative to spatial and temporal interactions of wildlife with their environment is a solid step towards the future direction of interdisciplinary science.

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