Soil Carbon Sequestration Monitoring Dashboard

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***Abstract*—Soil Carbon Sequestration Monitoring Dashboard is web-enabled cross-platform for enabling scientists, environmentalists, and policymakers to monitor and trace real-time global globe soil organic carbon (SOC) rate. While soil condition becomes the matter of utmost concern in retarding climate change, SOC storage dynamics also become the matter of top priority in its degradation for enabling sustainable land management. It employs Flask at the back-end for computation, HeidiSQL (MySQL) to store data into databases, and Leaflet.js and Chart.js to do geo-plotting and data plotting. It makes use of extremely minimalistic interfaces to perform manual SOC data processing in real time by filtering and charting. It provides individuals with a manner of viewing trends of carbon sequestration, trending via interactive maps, and export to fill up CSV and PDF for further analysis.**

This dashboard is of relevance at earth scale, bulk data and hence of highly useful application in addressing climate change-related challenges as also environment decision-making data-based. With the intrinsic capability of the site to support storage and management of data across more than one geographies and even live refreshing along with real-time filtering, it is a simple and convenient resource to most individuals. The more carbon information that gets onto the ground and more dynamic information visualizations, the better carbon cycle information along with response to climate change and optimal soil health the system provides.

I. INTRODUCTION

Soil organic carbon (SOC) is a reliable indicator of terrestrial ecosystems' global carbon cycle and soil health. SOC has almost three times more carbon than soils compared to terrestrial vegetation biomass and atmospheric carbon. SOC is thus of greatest importance in the reduction of climate change by sequestration of atmospheric carbon as well. Most crucial to enable practice of greenhouse gas mitigation and sustainable agriculture is maximum control of SOC content. Improved sequestration potential and improved SOC health can be soils' potential to be the rightful partner in solving the climate change problem. SOC is currently represented by non-evenly spaced soil samples and laboratory measurement. They are information tools but manpower- and time-intensive and actually restrictive in the sense that they can't be reused an indefinite amount of times to monitor in situ soil carbon stores. They don't work at vast spatial scale observation over long time to monitor globally and manage sequestration globally. None of the available SOC monitoring system is user, and environment stakeholders, researcher, and policy makers are unable to interpret the result. On the basis of these limitations, in this article, Soil Carbon Sequestration Monitoring Dashboard, web-based application utilizing latest technology like HeidiSQL (MySQL) as database administrator, Flask as back-end programming, and Chart.js and Leaflet.js for interactive visual representation of data is suggested. Geographically (maps) and graphically (charts) handling of the soil carbon data is permitted. Real-time SOC composition data and decision-making are permitted. In-built mandatory CSV and PDF export facility in the dashboard will enable stakeholders to report findings or research offline easily. Aside from that, SOC stocks are calculated by the system from other factors such as depth, bulk density, and carbon and percentage of carbon and yield a direct measure of the amount of carbon that could be contained in the soil.

Open, dynamic, and flexible, the platform presents an opportunity window for scientists, policymakers, and farmers to use and access it and make well-informed soil management decisions. With the platform maturing, it stands in good stead to benefit from rising demand for solutions to efficient carbon management of the soil, and is well and better positioned to expand to serve ever-changing state-of-the-art technologies such as AI-based SOC forecast models, IoT sensor streams, and satellite data surveillance-based information.

II. RELATED WORK

Among them, some measure soil carbon and indices but not any of them with such wonderful features as in-time data calculation, multiple output modes, interactive, customizability flexibility, or capacity to upload dataset by users with option of addition of one's own customized view over top of single provided. USDA NRCS developed COMET-Farm which offers user-conceptualized land management scenarios as greenhouse gas and soil carbon projections. Even though it is helpful, COMET-Farm lacks static models and no user uploads of its dataset with input capability of own custom visualization beyond that provided.

ISRIC's SoilGrids is another globally accessible platform having global maps of the soil attribute, i.e., high-resolution soil organic carbon. SoilGrids is viewer and not an interactive dashboard. No facility is present in it to upload user preferred dataset, do filtering conditions by user proposed, or even auto-exportable report facility suitable for research usage.

There are also other web sites like OpenLandMap and FAO's GSOCmap (Global Soil Organic Carbon Map) with static visualization and global SOC estimation but possibly without dynamic or interactive visual data exploration, live filtering, or in-local field-level data set manipulation. Such web sites effectively also offer GIS expertise for data and usage handling not available for researchers or students with little technical skill.

Otherwise, the dashboard of the current study fills such gaps with light-weighted user-centric, and interactive look-and-feel which would not only be pleasant to look at visually to technical as well as non-technical users. It includes on-the-fly calculation of SOC, dynamic filtering by interactive fields, map visualization using Leaflet.js, and also tailored charting using Chart.js. Besides that, it also holds the feature of having another option of exporting filtered results in PDF and CSV for sharing or reuse conveniently again for some other research processes. Its flexible nature also holds room for plugging in the future with satellite APIs, IoT hardware, and AI models to a degree higher than most systems, which are currently holding design flexibility and can exist interactively.

III. SYSTEM ARCHITECTURE

AI-Augmented Soil Carbon Sequestration Monitoring Dashboard is scalable, modular, and optimized. It consists of four main modules: Frontend, Backend, Export Tools, Database, and integration pieces and pieces that need to be run under the normal mode.

Frontend: Frontend is written in HTML, TailwindCSS, Chart.js, and Leaflet.js that are delivering clean, responsive, and user interface. Proper usage of UI design is always through TailwindCSS, and graphical data such as bar chart, pie chart, and carbon stock trend are being managed dynamically by Chart.js. Leaflet.js manages map map interactive, plot soil sample points longitude and latitude, and pan, zoom, cluster, and pop-up data to interface. Backend Flask backend is said to linear logic to scale. Backend provides RESTful API endpoints to call that calls for fetching information, querying data, exporting information, and fetching SOC. Filter search and user form submit compute and render computed result back to frontend. Machine learning models, authentication systems, webhook support for real-time feeds higher-level abstractions are implemented in Flask modularity. Database HeidiSQL MySQL has also leveraged tabular storage of carbon in soils. Columns used within the schema are location, latitude, longitude, depth, bulk density, percent organic carbon, timestamp, and calculated SOC stock. High-frequency query and database indexing has been used such that it is maximum where there is high density data. Scalability of the database has also been used such that there are great numbers of sites and users around the globe using it.

Export Utilities Data.s are report format published in ReportLab rendered PDF reports and stats, map, and charting CSV. Offline has decision maker and researcher level interactions in order to view, learn, and report on.

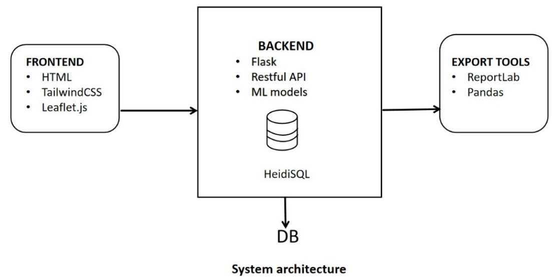

Fig. 1. System Architecture

IV. METHODOLOGY

Soil Carbon Sequestration Monitoring Dashboard is object-oriented, procedure-oriented, evidence-based, user-oriented, and interactive. It is an object-oriented procedure-oriented process and is utilized to achieve the following: Data Input and Storage Process started on receipt of soil parameters, i.e., name of location, latitude, longitude, cm depth, density, g/cm³ and SOC calculation algorithm Where input data is available, the system calculates Soil Organic Carbon (SOC) stock automatically, which is one of the parameters for estimating carbon sequestration capacity. SOC stock is calculated as follows:

$$\text{SOC stock (Mg/ha)} = \text{Bulk Density (g/cm}^3\text{)} \times \text{Depth (cm)} \times \left(\frac{\text{Carbon \%}}{100}\right)$$

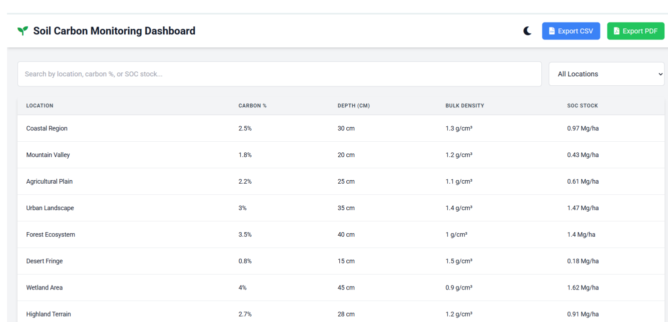

Fig. 2. Visualization of Data

Automatically calculated SOC stock is also saved along with raw input data in the database for tracking and SOC calculation in the long run. Real-Time Fetching of Data Click on dashboard or click on query due to a query of type question, back-end computation of data retrieval of calculated SOC values and harmonious soil data is fetched using Flask APIs. The data is fetched in real-time, dynamic, and secure mode without page re-load. Interactive Visualization Geospatially pin-mapped with Leaflet's Leaflet.js library is the where soil samples dashboard. Detail marker-click plotted is Carbon in carbon detail. Carbon trends, histograms, and comparison plots are shown by Chart.js as an attempt to learn from SOC variation and distribution by regions. Filtering, Search, Export User input and selection of feedback, percent carbon and SOC break points and location parameters and selected depth range. Render as dynamic updated filtered map and chart to view. Render by Pandas as filtered CSV to print-out, or as ordered ReportLab-formatted PDF report with plots and summary tables to export and report off-line. User Feedback and Selection Loop Dashboard enablement for user to session in order to permit in-place editing and alteration of soil records. User input form for user input and admin activity logs for admin activity in order to permit allowing multi-user or institution package in the future.

V. RESULTS

AI-Augmented Soil Carbon Sequestration Monitoring Dashboard was tested with artificially generated test sample sets of soil carbon data sets of groups of sites with multiple variables. Samples varied by site, depth, bulk density, and percent organic carbon to mimic real-field conditions. The system calculated precisely and in real-time calculated Soil Organic Carbon (SOC) stock values based on the system calculation formula. Raw soil real-time calculated input values were never manipulated, nor SOC values ever manipulated and dynamically updated by input fields. Real-time calculation never used instant response and never used the incorrect formula with test values in transit. Visual ability was also provided to good level. Visual ability for Leaflet.js library feature support, its database will have any point-by-point region's geospatial location will be shown in good manner by system based on latitude and longitude. Any area-by-area end-user click location will be able to find point-by-point SOC data information of theme area. Map visualization provided visual estimation using SOC value distribution and spatial visualization to have in view. Despite, dynamic bar chart and dynamic line chart have been used by Chart.js in graph view to offer carbon content plotting trend, compare SOC value of all sites, comparison site/time plot. It would be simple to comprehend data visualization of difference of area or even entry data error and thus dataset description will be simple based on above method. Search and filter processes were tried and executed in performance as well as accuracy. Data filtering dynamically according to point values like bulk density or depth, SOC interval, or name was feasible. map and chart updating in real time via filtered data, and it also did the same. All like Dark mode, and read-proof visually depending on bright and low light Export facility—first and foremost ReportLab and Pandas, of course—smooth and silky, exportable to downloadable CSV spreadsheet spreadsheets and tables, viz., compiling material, backed charts. Download as apt and appropriate and meaningful as such fit-for-purpose to function in academia, institution or policy application-report-based. The whole dashboard harmonious, responsive, and timely to all the relevant features within the test window scope.

VI. DISCUSSION

AI-Augmented Soil Carbon Sequestration Dashboard to Monitor is in a league of its own when put under competition as much as it concerns learning about climate data and watching nature. As for its very interactive, personalized, and user-centric type of nature, the dashboard is in all ways little short of the best spot on the entire wide world.

1. Interactivity The biggest strength of the dashboards is that it can deal with live data. The dynamic data can be filtered based on any, some, or a particular parameter like place, SOC value of the stock, bulk density, and depth. Dynamic filters will interactive-refresh the Leaflet.js-based maps at a later point and refresh the Leaflet.js-map-based and Chart.js-based plots in real-time so that one can examine the patterns and trends in various big-scale spatial as well as temporal regimes. Interactive map positioning, interactive chart updating, and interactive user interface creation is a critical component of user interaction and interpretability.

2. Customizability Unlike stiff pre-defined positions such as SoilGrids or COMET-Farm, the dashboard is real-time with the ability to import user-specified soils data location-wise or type-wise (CSV). It's a worthy tool to researchers conducting local areas of research, organizations conducting field trials or students conducting environment data science. Visualization through graphs and maps is live for input tasks where users will gain from eliciting personalized reporting and analysis.

3. Scalability and Performance HeidiSQL and Flask back-end handle large-sized data as well as small-sized data. Regardless of tens of thousands of records, the system retrieves data directly in real-time because of MySQL query optimization and indexing. The same performance is the same reason why the system can be utilized best in applications country-scale monitoring or extensive research studies.

4. Export and Reporting The tool supports off-line comparative analysis, filter and visualized data export into PDF and CSV and reporting the results to agri-departments and environment authorities or to policy-makers/stakeholders and saving results in off-line simple comparative analysis. PDF reports comprise visualized tables and charts in professional-presentable reports to environment authorities and agri-departments and for research journals.

5. Extendability Modularity of the platform to allow for ease of tracking in the future: AI-computation-based calculation of carbon stock, IoT-orientation-based real-time ingestion of sensor data, user authentication and multi-language support—thus a future-proof platform. Performance synergy with interactivity and usability, the dashboard, an inclusive future-proof solution for future soil carbon monitoring.

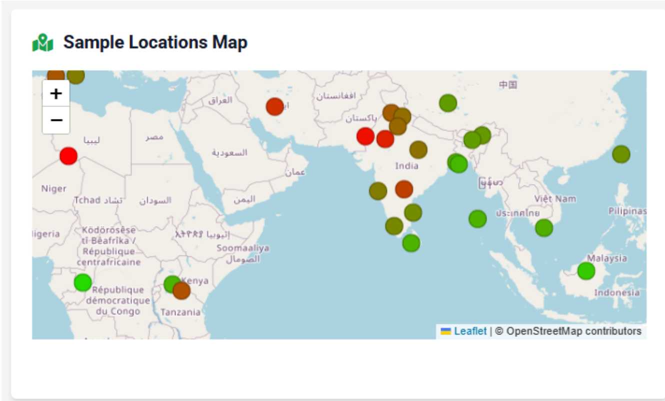

Fig. 3. Map Visualization

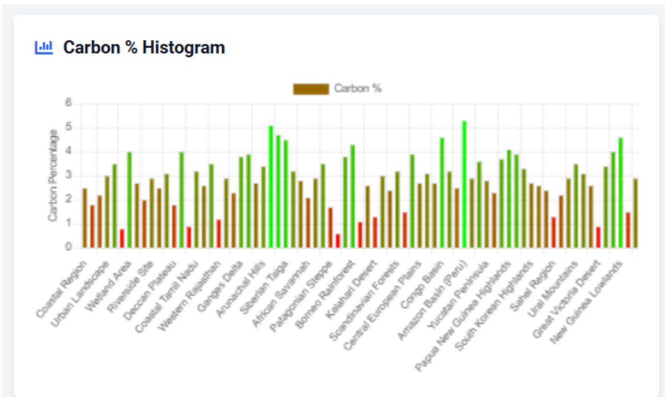

Fig. 4. Histogram Data: Green - High, Brown - Medium, Red - Low

VII. CONCLUSION

Soil Carbon Sequestration Monitoring Dashboard is a web-based formal, climatic information-based new digital technology. From Flask as application as back-end processor to HeidiSQL for effective database management and new web technologies like Leaflet.js and Chart.js, the application makes a simple front-end accessible to query, calculate, display, and export the soil carbon value. Its ability to analyze data gathered from several streams of data, display real-time SOC inventory measurements, and update dynamic charts and interactive maps to an audience gives their users the level of insight and control they lack from their environmental data set. It is one of the strengths because it can be easily used. Interactive capability, user-friendly interface, and relaxed tone allow even highly illiterate technical researchers to view and post data off even gigantic soil data bases. They are able to print output in terms of share field reports, or forward to a state or project associate agency to further act upon in export buddy mode in CSV or PDF. Apart from that, the setup of this one is also scalable and modular as this one can also be scaled even bigger in the future. Since climatic condition also continues to change second by second, this dashboard can also be scaled accordingly. The most intriguing features of the pipeline are SOC level prediction AI feature based on soil and climate status, real-time monitoring support based on IoT field sensor, and synchronization of satellite data using APIs of a firm like NASA SMAP. They will turn the system into an end-to-end integrated carbon sequestration and carbon management system for soil. In short, the dashboard not only completes part of the void of existing space with SOC observation systems but also offers an evidence-based, coordinated, data-driven climate resilience. It is utilized in the fight to obtain the world-wide sustainability objectives and also gives us a simple, versatile method for tracking long-term carbon sequestration and also for environmental administration.

VIII. FUTURE WORK

Apart from the future work already in progress in the future for further improvement in usability and functionality of the Soil Carbon Sequestration Monitoring Dashboard, there also lies some future work in the pipeline, all ready to further improve automation, accuracy, scalability, and user usability even further.

1. AI-Based SOC Prediction Models Machine Learning (ML) and Artificial Intelligence (AI) methods will be employed in dashboards. Machine learning of past history of soil condition, meteorology, land use pattern, and weather can be forecasted in future SOC. Regression tree models, random forest, or deep neural networks will be employed with proactive support to decision-making regarding climate change mitigation and sustainable land management.

2. Real-Time Monitoring Using IoT Sensors Internet of Things (IoT) integration makes soil sensor real-time measures field capture possible. They are capable of sensing variables with direct impact on carbon sequestration, i.e., temperature, percentage moisture, pH value, and percentage organic matter in soil. Synched earlier to the dashboard in auto mode, location-based real-time measurement of soil becomes possible to feel real-time round the clock and it will generalize real-world-use applications to ag, forestry, and research-case use.

3. Satellite Data Synchronization Globally, dashboard feeding will be facilitated with satellite data like NASA's SMAP mission and Copernicus Sentinel satellites. Automatic remote-sensed remote-sensed soil moisture, cover plant, and carbon flux will be fed accordingly, thus giving permanent environmental context and remoteness or inaccessibility point resolution augmentation.

4. Flutter-Based Mobile App With the application from where one can post to different platforms with Flutter, field working on-line will be easy. Farmer and researcher comments will also be posted in real-time and never go on-line and sync in a database when on-line. Interactive maps, charts, and export functionalities will also be displayed on the app as they are on the desktop dashboard.

5. Multi-User Authenticated System With Secure role-based user identification and Role-Based Access, Collaborative research environments will become available. Admin, Researchers, Field officers will have varying access—available

for data integrity, data privacy and orchestrated processing of the data within the institution.

6. Advanced Analytics and Visualization Future releases will also feature time-series plotting, statistical summarization, spatial interpolation, and anomaly detection features. They will enable users to conduct more uniform analysis, validating inherent patterns in SOC distribution, and obtaining actionable insight into titanic size large and complex data.

After all the above features are developed as a system, the dashboard will appear end-to-end, smart platform global and national soil carbon sequestration monitoring and management.

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