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REVIEW ARTICLE

A REVIEW ON APPLICATIONS OF UAV-BASED REMOTE SENSING FOR MAPPING SALINE AND WATERLOGGED SOILS: ADVANCES, CHALLENGES, AND FUTURE DIRECTIONS

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Abstract: Soil plays an important role in addressing global environmental concerns, underlining the impacts of climate change, food and water security, land degradation, and habitat loss for various species. Soil salinity and waterlogging are among the most widespread forms of land degradation, posing serious threats to agricultural productivity, ecosystem stability, and global food security. High soil salinity and water logging reduces crop productivity and degrade soil structure, creating a need for their monitoring and management. The conventional method of soil sampling and groundwater observations yield reliable information at individual locations, their usefulness for mapping soil salinity and waterlogging is limited by sparse spatial coverage, high operational costs, and infrequent data collection. These constraints make it difficult to adequately represent the spatial complexity and rapid temporal changes associated with salinity and waterlogging processes. Nowadays, UAV-based remote sensing overcomes these limitations by providing high-resolution, spatially continuous, and timely information, enabling more accurate delineation and monitoring of affected areas. These platforms offer a more effective approach for accessing soil salinity and waterlogging by using different type of UAV sensor and increase the accuracy of results.

Keywords: UAV remote sensing, Hyperspectral imaging, Multispectral imaging

INTRODUCTION

Soil salinity and water logging are the major forms of land degradation which affecting agricultural productivity, ecosystem stability, and global food security. Nowadays, it is estimated that more than 800 million hectares of land worldwide are affected by salinity and water logging problems which frequently co-occurs in irrigated and poorly drained landscapes, especially in arid and semi-arid regions (FAO, 2021). These soil conditions reduce crop yields, limit root development, disrupt nutrient uptake, and accelerate land abandonment and posing significant challenges to sustainable land management.

The Traditional methods of soil salinity and water logging accessing depend heavily on field surveys, soil sampling, and laboratory analyses. Even though these methods can give accurate results at specific locations, they require significant amount of time, effort, and resources, thus making the practical use of such methods difficult to apply across large or diverse landscapes and also the measurements taken directly in the field may often fail to capture the natural variability of salinity and soil moisture, which can change considerably due to small differences in land elevation, irrigation practices, and soil texture (Corwin and Lesch, 2013). Therefore, decisions based solely on ground observations may be limited, as they do not always reflect the full range of conditions present across the entire area.

Therefore, the Satellite remote sensing has been emerged as a powerful technique which greatly improved monitoring of soil degradation from local regions to global scales. But the Satellite data are also narrowed due to low spatial resolution, atmospheric effects, low revisit periods and mixed pixel effects, at least in the discontinuous agricultural regions. Such limitations reduce the efficiency of satellite images to follow the fine or early-stage trends of salinity and waterlogging as applied in the accuracy agriculture sector.

In the recent years UAV-based remote sensing has become a strong alternative, which is capable of replacing conventional remote sensing, as a replacement connects the ground survey with the satellite survey. UAV platforms have ultra-high spatial resolution imagery, flex-bright deployment, and flexible capture of data governed by the time and space requirement of the user. The combination of UAVs with advanced sensors such as multispectral, hyper spectral, thermal, and LiDAR systems have provided new opportunities for detailed soil mapping and monitoring (Manfreda *et al.*, 2018).

Soil Salinity and Water logging: Processes and Remote Sensing Signatures

Processes Leading to Soil Salinization and Waterlogging

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The salinization of the soil takes place when soluble salts are deposited in the soil profile, which happens as a result of the occurrence of natural processes. e.g. weathering of parent material, capillary rise of saline groundwater or as a result of human activity like poor irrigation control and poor and insufficient drainage (Rengasamy, 2006). Overuse of low-quality irrigation water with high evaporation rates on top of it enhances the rate of salt accumulation in the root zone, primarily in the arid and semi-arid conditions (Qadir *et al.*, 2007).

Waterlogging refers to the state whereby the soils have their pores filled with water over extended durations rendering oxygen unavailable in the root zone. The cause of this condition is usually shallow ground water tables, heavy rainfall, flat plains and incompetently constructed irrigation or drainage systems. It is possible to describe salinity and waterlogging as the tightly related processes, as with the increase in groundwater table often bringing dissolved salts to the ground surface, increasing the salinization (Corwin, 2021).

Effects on Soil Properties and Vegetation

Salinity and waterlogging have a massive impact on the physical, chemical and biological attributes of soils. Salt causes inhibition of water uptake by plants, ion toxicity, especially of sodium and chloride ions (Munns and Tester, 2008). Sodic conditions also cause worsening of soil structure as they spread clay particles and slow down the infiltration rates. (Rengasamy & Olsson, 1991). The salinity and waterlogging effects on vegetation involve less biomass, leaf turning, slowed growth, and the change of the canopy architecture pattern. Such responses of stress directly affect the property of surface reflectance and hence vegetation is the major indirect indication used by remote sensing in detecting soil degradation. In extreme situations, bare salt crusts can be developed which results in specific spectral characteristics of the soil which can be directly mapped.

Spectral Characteristics of Saline and Waterlogged Soils

The saline soils have specific reflectance values at the visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) wavelengths. The salt crusts are mostly light in color, hence reflecting a lot of visible bands; whereas certain absorption in the SWIR region is attributed to the evaporite minerals like gypsum and halite (Metternicht & Zinck, 2003). These characteristics have been extensively used in hyperspectral remote sensing investigations. Conversely, waterlogged soils have a lower reflectance at the NIR region because they have more surface water and water molecules absorb the reflectance. Infrared data, especially thermal ones, can be especially useful in the detection of waterlogged lands since the surface temperatures of saturated soils decrease in relation to those of well-drained soils under the conditions of the daytime (Allbed *et al.*, 2018). The spectral and thermal analysis of the soils analyzed increases the discrimination of the saline, waterlogged, and non-affected soils.

Overview of UAV Remote Sensing Technology

UAV Platforms for Soil Mapping

UAV platforms used in environmental and agricultural monitoring are generally classified as fixed-wing or multirotor systems. Fixed-wing UAVs are capable of covering large areas efficiently and are well suited for regional surveys; however, they require more space for takeoff and landing and offer limited at low altitudes (Colomina & Molina, 2014).

Multirotor UAVs, including quadcopters and hexacopters, provide greater operational flexibility, precise hovering capability, and vertical takeoff and landing. These features make them particularly suitable for detailed soil surveys, repeated monitoring, and field-scale assessments where high spatial resolution is required. As a result, multirotor platforms dominate UAV applications in salinity and waterlogging research (Manfreda *et al.*, 2018).

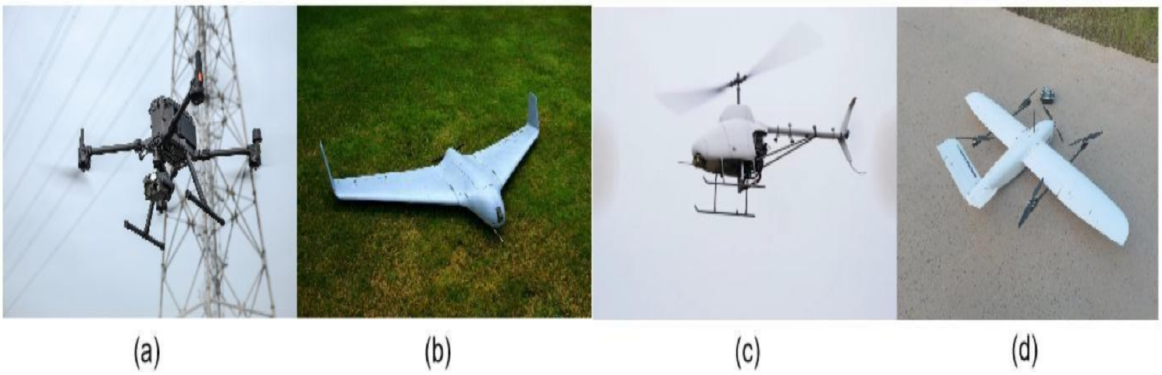

Figure 1. UAV platforms: (a) Multi-rotor UAV, (b) Fixed-wing UAV, (c) Unmanned Helicopter, (d) VTOLUAV

Sensor Types Relevant to Salinity and Waterlogging Detection

UAVs can be equipped with a wide range of sensors tailored to specific mapping objectives. RGB cameras provide high spatial detail and are useful for visual interpretation and surface pattern analysis.

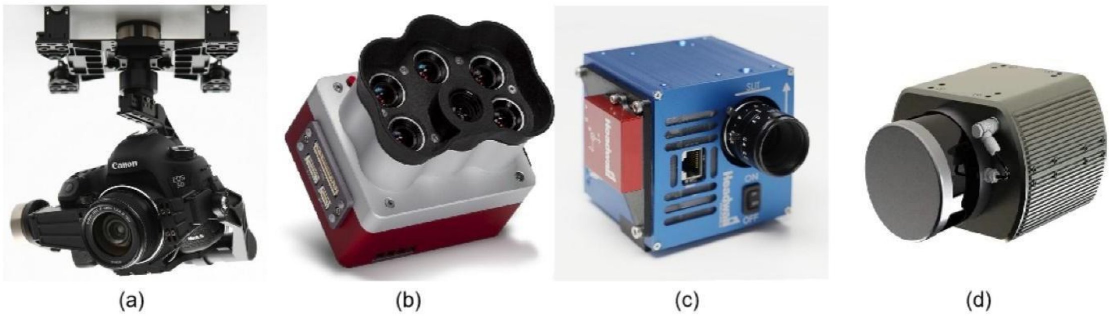

Figure 2. Sensors carried by UAVs: (**a**) RGB Camera, (**b**) Multi-spectral Camera, (**c**) Hyper-spectral Camera, (**d**) LIDAR

Multispectral sensors capture discrete bands in the VIS and NIR regions and are widely used to derive vegetation and soil indices related to stress and moisture conditions (Bendig *et al.*, 2015). Multispectral sensors mounted on UAVs typically capture reflectance in key spectral bands such as blue, green, red, red-edge, and near-infrared, enabling the derivation of indices related to vegetation stress and soil properties. Indices such as the Normalized Difference Vegetation Index (NDVI) and Soil-Adjusted Vegetation Index (SAVI) have been widely used as indirect indicators of salinity-induced crop stress, particularly in irrigated agricultural systems (Allbed & Kumar, 2013).

Hyperspectral sensors offer contiguous spectral information across hundreds of narrow bands, enabling detailed identification of salt minerals and subtle vegetation stress responses. Hyperspectral sensors provide enhanced capabilities by capturing narrow, contiguous spectral bands that allow direct identification of salt-related absorption features, especially in the shortwave infrared region. UAV-based hyperspectral imagery has demonstrated strong potential for distinguishing between different salt types and salinity severity levels, even in sparsely vegetated or bare soil conditions (Aasen *et al.*, 2018). Despite their advantages, hyperspectral systems remain constrained by higher costs, increased data complexity, and limited flight endurance. Although historically limited by cost and payload constraints, recent advances in lightweight hyperspectral sensors have increased their adoption in UAV-based soil studies (Aasen *et al.*, 2018).

Thermal infrared sensors play a crucial role in detecting waterlogged areas by measuring land surface temperature variations associated with soil moisture conditions. Saturated soils typically exhibit lower daytime surface temperatures due to higher thermal inertia and evaporative cooling, making thermal imagery particularly effective for identifying persistent waterlogged zones (Allbed *et al.*, 2018).

Thermal sensors are critical for detecting surface moisture while LiDAR provides high-resolution elevation data essential for analyzing micro-topography and drainage conditions. Elevation data derived from UAV-based photogrammetry or LiDAR further enhance waterlogging assessments by capturing micro-topographic variations that control surface runoff, ponding, and subsurface flow. The fusion of thermal and topographic data has been shown to significantly improve waterlogging detection accuracy.

UAV-Based Sensors and Data Acquisition for Saline and Waterlogged Soil Mapping

Flight Planning and Data Acquisition factors

Flight planning and data acquisition strategies are very important to ensure that UAV-based assessments of soil salinity and waterlogging are reliable. In contrast to satellite platforms, UAV surveys are very configurable and this feature enables researchers to optimize the spatial resolution, illumination conditions, and timing of the study based on the study objectives. The first factor that determines the sampling distance of the ground is the altitude of the flight, which should be chosen with care to ensure the little variability of the soil and vegetation is taken as well as ensuring that there is an efficient distribution. Flight altitudes of 30 to 120 m above the ground level have been effective in the resolution of micro-topographic features and surface patterns related to the salinity and water accumulation in most studies that were soil-oriented (Diaz-Varela *et al.*, 2015). Another essential aspect is image overlap because to have a successful photogrammetric reconstruction, high side and forward overlap is necessary. The commonly adopted overlaps of more than 70 percent in the direction of the flight and 60 percent in the lateral direction are to guarantee a reliable production of orthomosaic and elevation models. The time of UAV surveys is also significant. Flights are also normally carried out in clear sky conditions and near solar noon so that the effects of shadow and radiometric variability can be minimized. In the case of waterlogging, surveys immediately after irrigation events or rainfall can increase contrast between saturated and well-drained lands, and thus detecting waterlogging more successfully (Manfreda *et al.*, 2018).

Image Generation and Data Preprocessing

Raw UAV imagery is not ready to be quantitatively analyzed, it requires a couple of preprocessing processes. Radiometric calibration is necessary to transform the raw digital numbers into surface reflectance values that provide a comparable value across the sensors, as well as flight dates. This is often attained with calibration panels that have known properties of reflectance or with onboard irradiance sensors that consider the varying illumination conditions (Bendig *et al.*, 2015). Effects on the atmosphere are not as high at the heights of UAV flights as they are in satellite imagery, but the variation in illumination caused by the varying solar angles and cloud cover still needs to be addressed. (Colomina & Molina, 2014).

Analytic Techniques and Modeling

In the last decade, the shift of research at the level of simple visual interpretation of UAV imagery has been towards more sophisticated quantitative and data-based research. These approaches can be primarily divided into spectral index-based approaches, machine learning-based modeling, and multi-depth salinity estimation methods that rely on combined sources of data**.**

Salinity and Waterlogging Vegetation and Soil Indices

One of the oldest and most popular methods of determining soil salinity using UAV imaging is spectral index-based. They are mathematical expressions of a series of reflectance values of various bands in the spectrum, constructed to amplify features of a particular soil or vegetation, and to reduce background noise. Saline conditions determine the accumulation of salt in the soil, which influences the color, brightness of the surface, and the physiological activities of the plants that determine spectral reflectance patterns of the UAV sensors. Many experiments have found that salinity does not only modify the chlorophyll content, the leaf structure, and the water uptake of plants, which are measurable changes in vegetation reflectance, especially in the visible spectrum, red-edge spectrum and near infrared spectrum. The bands can be used to obtain indices that can then serve as proxy measurements of soil salinity, through the effects of salt-induced vegetation stress. To detect saline patches, reflectance-based indices that are sensitive to surface brightness and soil moisture have also been utilized on bare or sparsely vegetated soils. It has been shown that salinity discriminative or stress indices may be more sensitive than traditional vegetation indices including NDVI particularly in moderately stressed crops, as opposed to entirely degraded crops. (Metternicht & Zinck, 2003). In spite of the fact that spectral indices are fairly easy to compute and interpret, their effectiveness may be affected by soil moisture, surface roughness, type of crops, and the stage of their development. Consequently, there is a lot of current literature suggesting the use of a combination of multiple indices or combining them with additional data, to enhance reliability and strength of estimating salinity**.**

Statistical and Machine Learning Models

In addition to index-based methods, statistical and machine learning models have also seen an increment in using UAV data to estimate the level of soil salinity and waterlogging. The application of spectral features as related to measured electrical conductivity or moisture content of soil has traditionally been performed through the use of linear and multiple regression models. Non-linear relationships and complicated interactions between variables are however not easy to capture with these models (Corwin and Lesch, 2013). Random forests, support vector machines and artificial neural networks are machine learning methods which have been shown to perform better when working with high-dimensional datasets as well as non-linear trends. There have been recent reports of multispectral, thermal and combination accuracy of prediction being significantly better when multispectral and thermal are used. topographic variables in the ensemble learning systems (Zhang *et al.*, 2019). The models are mostly efficient in heterogeneous agricultural landscapes with salinity and water logging that are spatially different.

Ground Truth Data and Model Validation

Good ground truth data are mandatory in the process of calibration and validation of UAV-based models. The strategies of soil sampling usually imply the measurements of electrical conductivity, pH, moisture content, and ion concentrations in the representative sites within the area of study. These field measurements also give reference data, with reference to which the estimations of UAV are checked (Qadir *et al.*, 2007). Cross-validation is widely used and independent test datasets are often used to validate the models in order to determine the robustness and generalizability of the model. There are performance measures like the coefficient of determination (R2), root mean square error (RMSE), and mean error (MAE) that are commonly results. The research continuously highlights that the precision of UAV-based salinity and waterlogging maps is highly conditioned by the quality and their spatial representativeness of ground measurements (Corwin, 2021).

Applications and Case Studies

UAV-Based Mapping of Saline Soils in Agricultural and Arid Environments

UAV-based remote sensing has been widely applied to map saline soils across irrigated agricultural systems and arid landscapes where salinization poses a persistent threat to productivity. High-resolution multispectral and hyperspectral UAV imagery has enabled detailed delineation of salinity gradients within individual fields, revealing spatial patterns driven by irrigation practices, soil texture, and micro-topography (Allbed & Kumar, 2013). These fine-scale maps provide insights that are not achievable using conventional satellite imagery, particularly in fragmented or heterogeneous agricultural regions.

In arid and semi-arid environments, UAV hyperspectral data have proven effective for identifying surface salt crusts and evaporite deposits, even under sparse vegetation cover. Several studies have demonstrated strong correlations between UAV-derived spectral features and laboratory-measured soil electrical conductivity, confirming the reliability of UAV platforms for quantitative salinity assessment (Metternicht & Zinck, 2003; Aasen *et al.*, 2018). Such applications highlight the value of UAVs for early detection of salinity hotspots and targeted soil reclamation efforts.

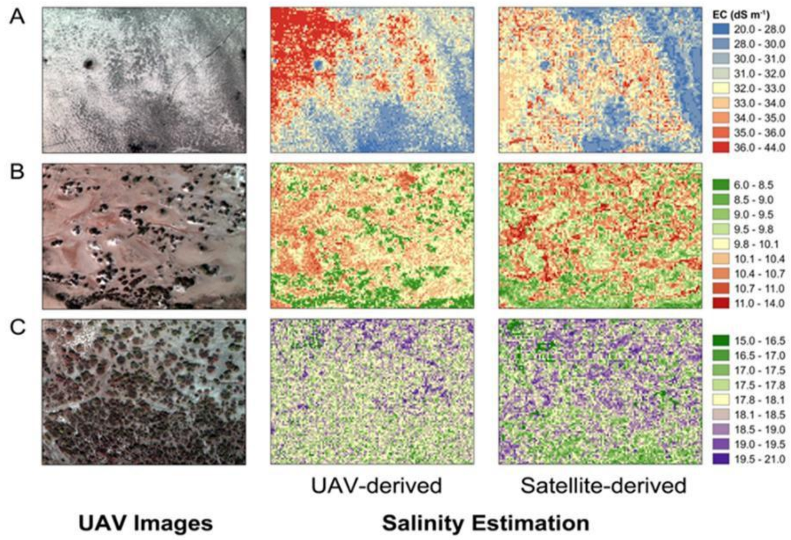

Figure 1. UAV hyperspectral images and derived soil salinity maps compared to coarser satellite-based salinity maps for three study fields (A, B, C). (Hu *et al.*, 2019)

Detection and Monitoring of Waterlogged Soils

Waterlogging detection has benefited substantially from the integration of UAV-based thermal and elevation data. Thermal imagery acquired during daytime conditions has been used to identify saturated soils through reduced land surface temperatures, enabling rapid mapping of poorly drained zones following irrigation or rainfall events (Allbed *et al.*, 2018). When combined with multispectral indicators of vegetation stress, thermal data improve discrimination between temporary surface wetness and persistent waterlogging.

Repeated UAV surveys have also facilitated temporal monitoring of waterlogging dynamics, allowing researchers to track the expansion or contraction of saturated areas across seasons. Digital elevation models derived from UAV photogrammetry have been instrumental in linking waterlogged zones to subtle topographic depressions and drainage constraints, providing actionable information for drainage design and land leveling interventions.

Advantages of UAVs Over Conventional Field Methods and Satellite Sensing for Soil Salinity and Moisture Mapping

Monitoring soil salinity and moisture is essential for understanding soil health, managing irrigation, and ensuring sustainable agricultural production. Traditionally, soil monitoring has relied on **ground-based sampling and laboratory analysis**, which, although accurate at specific points, suffer from severe limitations in spatial coverage and temporal frequency. Satellite remote sensing provides a broader perspective but has its own set of challenges. UAVs (drones), positioned between ground surveys and satellite systems, offer significant advantages for both **precision and operational flexibility**.

Higher Spatial Resolution

One of the most important advantages of UAV remote sensing is its ability to collect ultra-high spatial resolution imagery—often at sub-meter or even centimeter levels—which is crucial for capturing fine-scale variability in soil salinity and moisture. Soil salinization and moisture patterns often occur at field and sub-field scales, exhibiting patchy distributions that coarse satellite pixels (10–30 m or larger) cannot resolve accurately. Studies comparing UAV and satellite data for soil salinity show that UAV-based models significantly outperform satellite-based models in precision, often with higher coefficients of determination (e.g., R^2 ~0.89 for UAV vs R^2 ~0.63 for satellite) and lower error metrics when estimating salt distribution at field scale.

Because UAVs fly at low altitudes, they reduce the mixed-pixel problem common in satellite imagery, where one pixel may represent multiple land covers (soil, vegetation, water), which blurs the soil signal. This enhanced detail enables more accurate mapping of soil variability even in heterogeneous landscapes.

Temporal Flexibility and On-Demand Data Collection

Conventional soil surveys require intensive labor and are typically conducted infrequently, due to cost and logistical constraints. In contrast, satellites have fixed revisit periods (e.g., 5–16 days for Sentinel or Landsat), which may not align with critical soil or crop conditions such as post-irrigation infiltration, rapid salinity changes, or moisture flux after rainfall.

UAVs provide **on-demand data acquisition**, meaning they can be deployed precisely when and where needed to capture conditions at critical times, such as during drought stress, irrigation scheduling, or soil reclamation activities. This temporal flexibility makes UAVs particularly useful for monitoring dynamic processes like soil moisture changes or rapid salt movement into the root zone.

Sensor Versatility and Customization

UAVs can carry a wide range of sensors tailored to soil assessment tasks:

Multispectral sensors that capture reflectance in visible and near-infrared bands useful for vegetation and soil indices.

Hyperspectral systems with many narrow spectral bands capable of detecting subtle soil chemical differences. For example, UAV-borne hyperspectral imagery has been shown to produce more accurate soil salinity estimates (with lower RMSE and higher concordance) than satellite multispectral sources.

Thermal cameras to detect variations in surface temperature that correlate with soil moisture and water stress.

LiDAR or photogrammetry to derive precise terrain and micro-topographic information that influences water accumulation and drainage.

This range of payload options allows UAVs to gather complementary data types in a single flight mission, enabling more comprehensive soil and moisture analysis than conventional methods or satellite sensors.

Enhanced Model Accuracy through Data Fusion

Integration of UAV data with satellite imagery can improve large-area monitoring. UAV data can be used to **calibrate and upscale satellite models**, correcting the coarse satellite output and yielding higher accuracy for broad-scale soil monitoring. For instance, combining UAV-derived high-resolution data with satellite imagery improved the satellite inversion model's R^2 from 0.63 to 0.787 and increased spatial agreement with ground truth from ~76% to ~90%.

This synergy highlights how UAVs can enhance large-scale monitoring not by replacing satellites but by calibrating and supplementing them to combine high precision and wide coverage.

Cost and Operational Efficiency Compared to Conventional Field Surveys

Traditional soil salinity and moisture assessment relies on systematic ground sampling, laboratory analysis (e.g., measuring electrical conductivity), and extensive field labor. This approach is time-consuming, expensive, and difficult to repeat at high frequency.

UAV surveys, although requiring initial equipment investment, significantly reduce long-term costs for repeated monitoring. They allow large areas to be surveyed quickly with minimal human labor on the ground, which improves safety in difficult terrain and reduces operational risk. UAV systems are also easier to mobilize and can be flown at relatively low cost compared to chartering manned aircraft for aerial surveys.

Improved Sensitivity to Soil and Vegetation Interactions

UAVs excel at capturing the interaction between soil conditions and plant responses at fine scales. Soil salinity and moisture influence plant physiology, expressed through changes in canopy reflectance and temperature. UAV imagery can detect these subtle changes in vegetation indices or thermal patterns that often precede visible stress signs, enabling early detection of problematic zones for intervention or irrigation adjustments.

Challenges and Limitations

Operational and Environmental Constraints

In spite of the mentioned advantages, UAV systems have a number of operational constraints that limit its widespread use. Flight endurance and payload capacity are limited which limits its coverage range, especially when carrying hyperspectral or thermal sensors. Wind, precipitation, extreme temperatures are also sensitive factors in UAV operations that may have an impact on flight safety and quality of data (Colomina & Molina, 2014). The presence of thick vegetation cover, roughness of the surface and unstable light contribute to the further complexity of the interpretation of UAV imagery. These limitations indicate the need to pay special attention to the design of the survey and the importance of realistic expectations when it comes to the applicability of the data.

Information Processing and Technical Complexity.

UAV Imagery is high-resolution, which implies that large amounts of data produced by this method consume a lot of computing power and technical skills to process. Photogrammetric reconstruction, radiometric calibration and sophisticated modeling procedures may be slow and technically challenging. These requirements are still a major obstacle to many end users, especially the local agencies and smallholder farmers (Manfreda *et al.*, 2018). Streamlining the operations by automating, processing in the clouds and using standardized protocols is thus a significant field to be developed in the future.

Regulation and Economic Factors.

The regulatory systems in place that govern the operations of UAVs are diverse across nations and may curtail the level of altitude, range covered, and the flexibility of operations. Flight permissions can be costly, in both time and cost, especially in cases of large scale or recurring surveys. Moreover, the prices of the UAV platforms, sensors, and specialized software, in particular, hyperspectral and thermal ones, are still prohibitive to some users (Zhang and Kovacs, 2012). These regulatory and economic considerations should be put into serious consideration when considering the feasibility of the UAV-based soil monitoring programs**.**

Future Trends and Research.

The UAV Sensor Technology Innovations.

The fast development of the technology of UAV sensors will considerably contribute to the detection and monitoring of the saline and waterlogged soils. Hyperspectral and thermal sensors with low power consumption have already been developed, increasing the payload capacity in UAVs, which allows them to take longer flights and cover a larger area (Aasen *et al.*, 2018). In the future designs of sensors, spectral resolution in the short wave infrared band will be enhanced, this is important in the direct determination of salt minerals and soil moisture dynamics. Simultaneously, the advancements in onboard GNSS and inertial measurement units will advance the accuracy of geolocation, thus allowing a more reliable multi-temporal analysis. Such technological advancements will diminish the operational limitations and expand the possibility of soil mapping using UAVs to conduct regular agricultural and environmental monitoring.

Applications of Artificial intelligence and Deep Learning.

Deep learning and artificial intelligence are becoming one of the transformative tools of UAV-based mapping of soil conditions. Artificial intelligence systems can also detect intricate spatial and spectral features, such as salinity and waterlogging, in high-resolution images with deep learning models and identify all these features on different terrains without having to be trained to generate these features by humans (Zhang *et al.*, 2019). Deep learning, in comparison to conventional machine learning methods, provides a more flexible way to process raw imagery and multi sensor data fusion. Nevertheless, these approaches present emerging issues on data needs and computational and model interpretability. Future studies are required on how to create transferable models that are reliably operating across regions, seasons, and explainable AI solutions which enhance transparency and user confidence. These concerns will be crucial to the process of making operational tools out of methodological advances.

Cloud based platforms and real time processing

Another new trend with considerable prospects of operational use is the integration of UAV systems with real-time data processing and cloud-based systems. The development of edge computing and wireless data transmission is allowing the creation of near-real-time orthomosaics and analytical products, minimizing the gap between the collection of information and the decision-making process (Manfreda *et al.*, 2018). Data sharing, collaboration, and scalability are also facilitated by the cloud-based processing platforms to enable the use of UAV-obtained soil maps by bigger agricultural decision-support systems. These advancements are specialized especially to the early warning systems to reduce risks of salinity and waterlogging in case of climate variability.

Precision Agriculture/Land Management Implications.

Saline and water-logged soil mapping by UAVs has immense application in decision-support of precision agriculture. The high-resolution spatial data allows site-specific irrigation scheduling, drainage design, and the application of amendments in the soil, which minimize the input costs and the negative effects of the environment at the same time. Focusing on the areas of impact, farmers will be able to maximize the efficiency of resource utilization and productivity (Corwin, 2021). At more macro scales, the UAV-products are applicable in the land management, policy formulation since the products are timely and precise in informing about the pattern of soil degradation. UAV-based early warning mechanisms can be used to provide prior action before disaster strikes to minimize the economic losses in the long run and help in the sustainable intensification. When incorporated into the local land management systems, UAV technology will increase transparency, accountability, and decision-making that is evidence-based.

CONCLUSIONS

This review has synthesized recent advances in UAV-based remote sensing for mapping and monitoring saline and waterlogged soils, highlighting significant progress in sensor technology, analytical methods, and practical applications. UAV platforms offer unparalleled spatial resolution, operational flexibility, and multi-sensor integration capabilities that address key limitations of conventional field surveys and satellite remote sensing.

The reviewed literature demonstrates that UAV-based approaches are highly effective for detecting fine-scale salinity gradients and waterlogging patterns, particularly when multispectral, hyperspectral, thermal, and topographic data are combined with machine learning models. Despite remaining challenges related to cost, regulation, and data processing complexity, ongoing technological and methodological innovations are rapidly expanding the operational viability of UAV systems.

Overall, UAV-based remote sensing represents a transformative tool for soil degradation assessment and management. Its continued integration into precision agriculture and sustainable land management strategies will be essential for addressing the growing challenges of soil salinity and water logging in a changing climate

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