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AHP and fuzzy logic geospatial approach for forest fire vulnerable zones

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A B S T R A C T

Fires are devastating risky events in forests, having a negative effect on resources, biodiversity, economics, animal life, and putting people in danger. The goal of this study is to use geospatial techniques to identify areas in Jordan that are at risk of forest fires. The research area extends 50 kilometers north and 15 kilometers east from the Dead Sea. The forest fire risk zones map was developed using six factors: land cover class, aspect, proximity to settlements, elevation, slope, and proximity to roads. All of the factors have been selected based on their fire sensitivity or capacity to cause fire. In this study, a Turkish model with fuzzy logic and Analytical hierarchy analysis (AHP) was utilized to classify the area into five categories of risk ranging from very low to very high. According to the findings, approximately 12.12% of the study area is classified as very low risk, 25.54 % is classified as medium risk, while 12.84% is classified as very high risk. Over the last ten years, the map has been confirmed by prior fire occurrences using data from civil defense archives. This conclusion was very useful in gaining an understanding of the geographical distribution of fire-vulnerable zones. The research found that the GIS approach combined with AHP and fuzzy logic is a useful tool for estimating such kinds of maps.

1. Introduction

About a third of the land area on Earth is covered by various types of forests. Forests are one of the vital natural resources because they are responsible for providing services and products to ecosystems like water, food, and shelter. Additionally, forests have a crucial part in the preservation of soil and biodiversity (Morales-Hidalgo *et al.*, 2015). It's also an interwoven ecosystem that's intrinsically related to human existence, so any disturbance will have a negative impact on life and stability. Unfortunately, fires, droughts, overgrazing, erosion, land removal, growing urbanization, tourist pressure, and forbidden logging and firewood gathering are all contributing to deforestation. Fires, on the other hand, are the most pervasive and long-term threat to forests, whether caused by natural or man-made reasons. A forest fire harms the natural environment by releasing hazardous air pollutants, emitting greenhouse gases, and destroying flora, as well as affecting the beauty of nature, animals, and grasslands, resulting in economic, social, and environmental damages. To mitigate and minimize forest fire hazard, all necessary procedures, as well as a fire action plan, must be designed and developed. To demarcate the forest fire risk zones, numerous studies employed geospatial approaches since they are cost-effective and time-saving. In this study five factors were employed, namely: landcover, elevation, distance from the settlements, slope, aspect and distance from the roadways. Anteur *et al.* (2021) did a study in Algeria on a similar subject. Nadjla *et al.* (2020) also employed a Turkish model based on six parameters: flora biomass, slope, elevation, aspect, proximity to roads, and proximity to urban areas. Kumari and Pandey (2020 employed AHP technique with weighted-sum-method (WSM) by forest fuel, bare soil index, settlement, road, elevation, aspect, and slope to map forest fire risk in India. Gheshlaghi (2019) employed ANP approach to link forest fire parameters and spreading of fires based on NDVI, yearly temperature, annual rainfall, land cover, altitude, slope, slope aspect, wind speed, vicinity to settlements, and vicinity to roads. While Youcef *et al.* (2020) and Hasheminasab

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et al. (2017) employed the Forest Fire Risk (FFR) technique, which takes into account a variety of characteristics at various research sites. However, Hasheminasab *et al.* (2017) found that the given model is ineffective in Iran. Ajin *et al.* (2017a) employed the Modified Fire Risk Index (MFRI) technique on the Southwest Indian Peninsula, which took into account six factors: slope, land cover type, proximity to towns, closeness to roadways, aspect, and elevation. In Iran, Eskandari (2017) developed a fuzzy logic algorithm with AHP to calculate the importance of the four primary criteria namely; man-made variables, biologic, climatic, and topographic variables, in addition to their 17 sub-criteria in forest fire. According to Ajin *et al.* (2016) and (2017b), a Fire Risk Index (FRI) model was established utilizing criteria such as land cover type, slope, elevation, distance from road, and distance from settlements for the identification of forest fire risk regions. Ariapour and Mohamed (2014) made use of the AHP model in order to decide which factors would be included in the study. These characteristics were ambient temperature, precipitation, evaporation, land-use, slope, aspect, proximity to settlement, proximity to roads and stream lines. While Adab *et al.* (2013) used the Structural Fire Index (SFI), Fire Risk Index (FRI), and a new Hybrid Fire Index (HFI) to delineate fire risk based on vegetation moisture, elevation, aspect, slope, proximity to settlements, and distance from roads, the HFI outperformed the other two indices in terms of accuracy.

In this work, geospatial methods are utilized to develop a fire risk thematic map for a study area in Jordan, which will serve as a solid reference for detection, control, and protection. In this work, we chose the Turkish model because of its applicability to Mediterranean areas and ease of implementation, since it does not need a lot of data, particularly for forest fires.

1.1 Study Area

The study area lies about 30 kilometers northwest of Amman, at latitude 32°01'19.4" N and longitude 35°38'52.4" E. The study area extends 50 kilometers north and 15 kilometers east from the Dead Sea. This is due to the fact that this section holds the majority of the flora, whereas the remainder is primarily desert as reported by Jamhawi *et al.* (2017) who described it as having rough topography, distinct hills and deep valleys. It is necessary to mention that the study area has an altitude ranging from -396.068 to 1152.59 meters, as shown in Fig. 1.

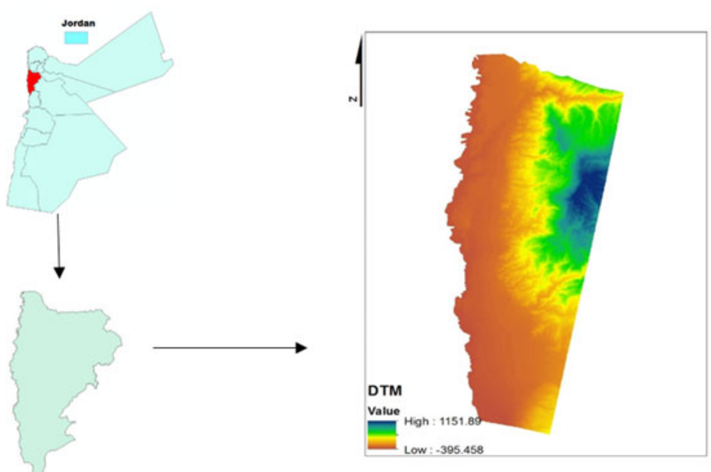

Fig. 1. Location map of the study area

2. Materials and Methods

The used model in this study combines AHP, GIS and remote sensing. The model's parameters responsible for starting and spreading forest fires were extracted from satellite images and digital elevation models. This requires integration of factors such as land cover types and proximity to settlements and roads, elevation, slope, and aspect. Fig. 2 shows the flow chart of the followed procedure including generation of digital elevation model, extraction of proximity networks, image classification to extract landcover map, and weighting the factors using AHP analysis.

The following summarizes how the research was carried out:

1. A detailed analysis of the previous research on forest fire management was carried out.
2. Categorization of the gathered satellite images in order to produce a map of the settlements
3. Identification and extraction of the road network from satellite pictures
4. Creation of digital elevation and digital terrain models using CARTOSAT satellite images as the source material.
5. Extraction of morphometric characteristics from the DTM, including slope and aspect.
6. Creation of the AHP model and the subsequent weighting of the parameters.
7. Constructing the matrices for doing pair-wise comparisons.

8. The development of a fuzzy appearance in the computed weights
9. Producing a priority vector for the judgments matrices and determining whether or not the judgments are consistent by computing the consistency ratio (CR).

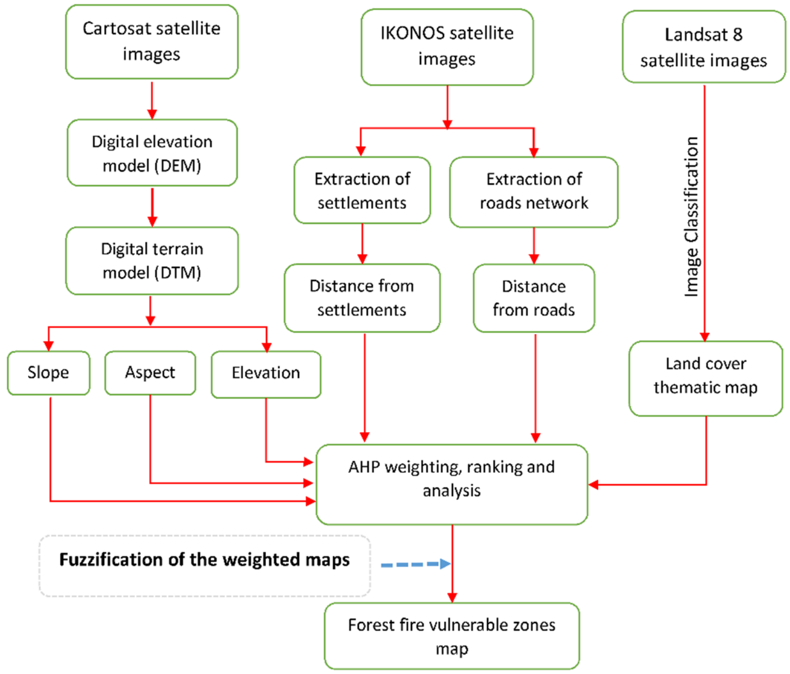

Fig. 2. A flow chart of the employed methodology

2.1 Modified Turkish Model

The developed forest fire Turkish model by Erten *et al.* (2004) and Dong *et al.* (2005) has been utilized in this study to map fire forest vulnerable zones in Jordan. Classes of vegetation cover, elevation of the area, slope and aspect, the, and proximity to roads and settlements are all parameters in this model. In the current research, however, land cover type will be used instead of vegetation type as the variation in land cover classes is obvious. The potential risk of forest fires was mapped using the Geospatial techniques, which included superimposing weighted layers on top of each other.

2.2 AHP Model

The Analytic Hierarchy Process, or AHP for short, is a measuring theory that makes use of expert opinion to build priority scales. This theory of measurement is based on pairwise comparisons. The comparisons are carried out with the use of an absolute judgment scale, which demonstrates the degree to which one component is superior to another in terms of a certain quality. A standardized method is used in the AHP calculation in order to provide an indication of the relative significance of each criterion in terms of pairwise comparisons. (Saaty, 1980, 2008). After that, the values are transformed such that they correspond to their respective weights in a matrix, which ranges from 10 to 100 depending on the potential level that the class has in terms of forest fire site selection. These weights were assigned based on literature review carried out in disciplines that are connected to this one.

The last phase of the AHP research is to compute the Consistency Ratio (CR), which evaluates how consistent the assessments have been in comparison to massive samples of random judgments. If the CR is much greater than 0.1, the decisions cannot be trusted since they are too close to being completely random. In this case, the exercise is either pointless or it should be done again (Coyle, 1989). In conclusion, the AHP analysis is going to be delivered in the stages that are as follows:
1: Principal Eigenvalue (λmax) is obtained using the eigenvector approach.
2: The Consistency Index (CI) can be determined by utilizing the equation that can be found here (Saaty, 1980):

$$CI = (\lambda max - n)/(n - 1)$$

where n denotes the total number of contributing parameters.

3. The formula for calculating the consistency ratio (CR) is as follows (Saaty, 1980):

$$CR = (CI)/(RCI)$$

where RCI stands for the random consistency index that represents the importance of each parameter as a scale of nine points. In this research, we made use of the Turkish model due to its adaptability to places around the Mediterranean and its ease of execution due to the fact that it does not need a large amount of data, particularly for that which is associated with forest fires. Table 1 is an overview of the approved criteria and weights:

Table 1
The approved criteria and weights of the used model

Factor	Classes	Values	Weight	Risk degrees
Land cover type	Water body	1		Very low
	Rocks	2		Low
	Built up	3	7	Medium
	Soil	4		High
	Vegetation	5		Very High
Slope (degree)	0-2.26	1		Very low
	2.27-4.52	2		Low
	4.53-7.54	3	5	Medium
	7.55-11.8	4		High
	11.90-38.4	5		Very High
Elevation (m)	(-400) - (-150)	1		Very low
	(-150) - 100	2		Low
	100- 500	3	5	Medium
	500-700	4		High
	700- 1200	5		Very High
Aspect	Flat	1		Very low
	North	2		Low
	Northeast	3	5	Medium
	East	3		Medium
	Southeast	4		High
	South	5		Very High
Distance from roads (m)	>3000	1		Very low
	2000-3000	2		Low
	1000- 2000	3	3	Medium
	500- 1000	4		High
	0- 500	5		Very High
Distance from settlements (m)	>1500	1		Very low
	1000- 1500	2		Low
	700- 1000	3	3	Medium
	300- 700	4		High
	0- 300	5		Very High

There is a significant correlation between forest fires and land cover, which is found on Earth's surface. Forest fires are fueled by vegetation, which is the most effective land cover. The flammability of various kinds of vegetation varies. Because dry and thick vegetation are more likely to catch fire, they are more likely to burn down. As shown in Fig. 3, the land cover categories in this research region include vegetation, built up (settlements), rocks or soil, and a water bodies.

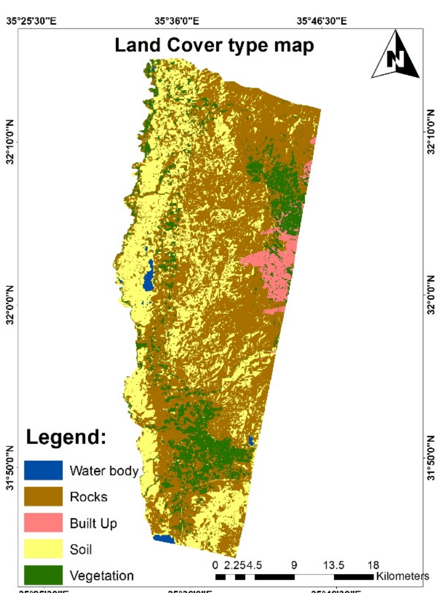

Fig. 3. Land cover classes map of the study area

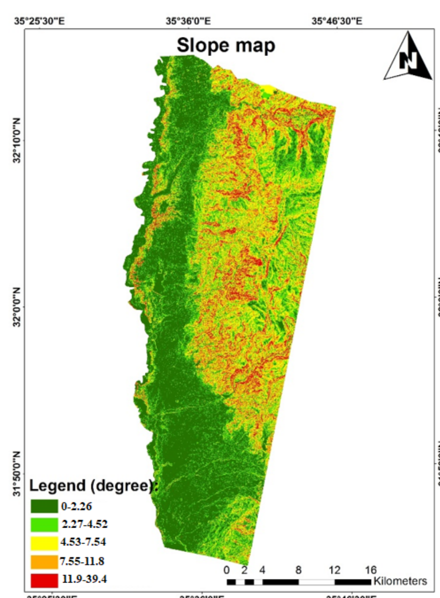

Fig. 4. Slope map of the study area

As the fire spreads, slope is the most crucial topographical feature to consider. The flames advance quicker up the hill and more slowly back down it. Consequently, the pace of forest fire spread rises as a result of water loss and more effective convective preheating on steeper slopes. With respect to the slope classifications indicated in Fig. 4. the study area has five distinct zones: 0-2.26 , 2.27-4.52, 4.53-7.54, 7.55-11.8 and 11.90-38.4. As altitude increases, the landscape steepens, making wind power more viable. There are several advantages to battling small forest fires at higher elevations, whether they are caused by lightning or human activity. Compared to the lowlands, lightning strikes occur more often at higher elevations. Forested locations with high elevations are more prone to wildfires because of this. The research area is subdivided up into five distinct groups, ranging in height from -1400 meters to 1200 meters as shown in Fig. 5.

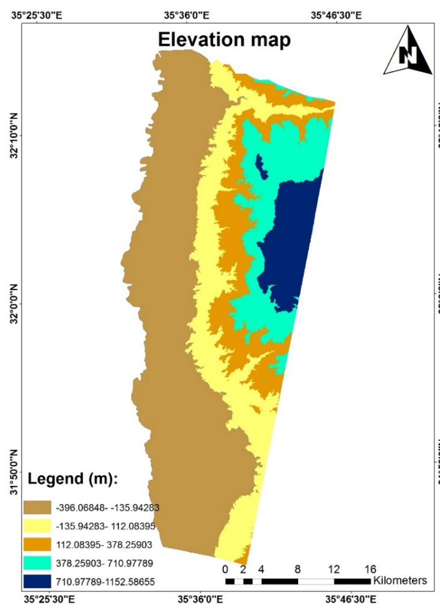

Fig. 5. Elevation map of the study area

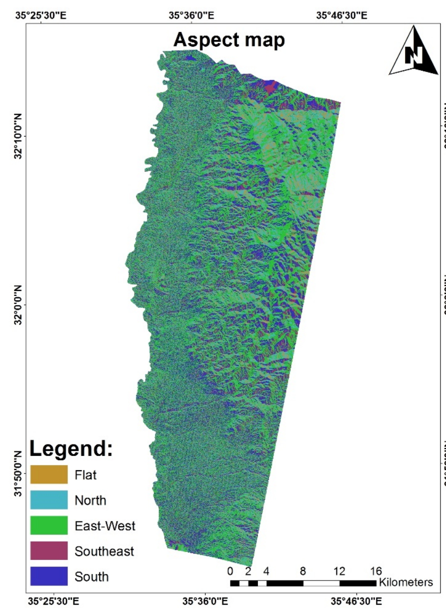

Fig. 6. Aspect map of the study area

In the Northern Hemisphere, a slope that faces south is more subject to wildfires than a slope that faces north because aspect plays a role in this susceptibility. This is due to the fact that slopes facing south get more sunshine and are thus drier than those facing north. As a result, the southwest-facing slopes are the most susceptible, while the northeast-facing slopes are the least vulnerable. Vegetation in the region is also affected by this factor. Dryer conditions on the south-facing slope foster the establishment of less hardy plant species like sedges and sagebrush. Fig. 6 shows the study's aspect map. Fires are more likely to break out in areas near major roadways. Some unplanned recreational activities are to blame for the frequent fires in this region. Using the roads, travelers may access woodland regions and set fires. However, wildfires may be started deliberately or accidentally by forest visitors and tourists who neglect their recreational activities. Fires are more likely to break out in areas near human settlements. As shown in Table2. The region has been divided into five categories based on the distribution of human settlements.

2.3 Fuzzy Logic Approach

This work utilizes Fuzzy Logic (FL) to construct the forest fire vulnerable map. The research area is subdivided up into five distinct groups, from the most disadvantaged to the most advantaged, based on the relative importance of several GWPZ criteria; all maps and parameters are linked together using the AND operator. It is shown in Figure 7. that the Mamdani Fuzzy Inference technique (MFIS) is used in this study. This approach is widely accepted as the go-to for fuzziest issues. Fuzzy set theory was used by Mamdani and Assilian (1975) to create MFIS, which was based on (Zadeh, 1975). This approach consists of the following steps: First, randomization is introduced into the entries. Then the rules of the model are also included in this section. After that, as a last point, adherence to the rules (inference), and Defuzzing the values that were generated after being fuzzed is the fourth step.

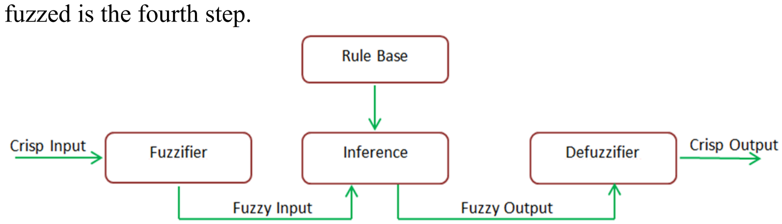

Fig. 7. Flow chart showing the application of fuzzy logic

Fuzzy logic was used to assign weights to the various classes of each parameter, as well as the results are shown in Table 2. according to the Fuzzy number associated with each parameter. The weighting and classification criteria that are utilized in AHP are precisely the same as those that are employed in this context.

Table 2
Fuzzy number of each classes and their corresponding ranking

Factor	Classes	Fuzzy Number	Ranking
Land cover type	Water body	0.19	Very low
	Rocks	0.33	Low
	Built up	0.43	Medium
	Soil	0.51	High
	Vegetation	0.65	Very High
Slope (degree)	0-2.26	0.72	Very low
	2.27-4.52	0.64	Low
	4.53-7.54	0.52	Medium
	7.55-11.8	0.24	High
	11.90-38.4	0.12	Very High
Elevation (m)	(-400) - (-150)	0.11	Very low
	(-150) - 100	0.26	Low
	100- 500	0.34	Medium
	500-700	0.56	High
	700- 1200	0.62	Very High
Aspect	Flat	0.14	Very low
	North	0.51	Low
	Northeast	0.23	Medium
	East	0.37	Medium
	Southeast	0.52	High
	South	0.64	Very High
Distance from roads (m)	>3000	0.22	Very low
	2000-3000	0.34	Low
	1000- 2000	0.39	Medium
	500- 1000	0.43	High
	0- 500	0.54	Very High
Distance from settlements (m)	>1500	0.18	Very low
	1000- 1500	0.25	Low
	700- 1000	0.37	Medium
	300- 700	0.44	High
	0- 300	0.53	Very High

3. Results and Discussion

AHP and Fuzzy Logic Geospatial Approach is used to utilize thematic map layers for parameters such as type of land cover, slope, aspect, altitude of the area, proximity to roads, and proximity to settlement to create the forest fire vulnerable map. Fig. 8. represents a map of forest fire vulnerable zones of the study area in which areas with a very high fire hazard risk make up 12.84 % of the total area, while 26.226 and 25.54 % of the area are high to medium fire risk zones. Around 23% of the area is classified as low and the rest as very low fire risk areas. The research found that severe topographical conditions and proximity to settlements increase the risk of the fire. This proves that the fires in the study area mostly started by people. The developed map has been verified by historical data obtained from the archives of the general directorate of civil defense in Jordan (PSD, 2020) as shown in Table 3.

Table 3
Fire risk zones percentage with number of fire occurrences (PSD, 2020)

Fire Risk Zone	Area (km^2)	Area (%)	Number of fire incidences	Percentage of fire incidences
Very Low	106.09	12.12	3	10
Low	203.34	23.23	5	16.67
Medium	223.51	25.54	11	36.67
High	229.86	26.26	7	23.33
Very high	112.38	12.84	4	13.33
Total	875.18	100	30	100

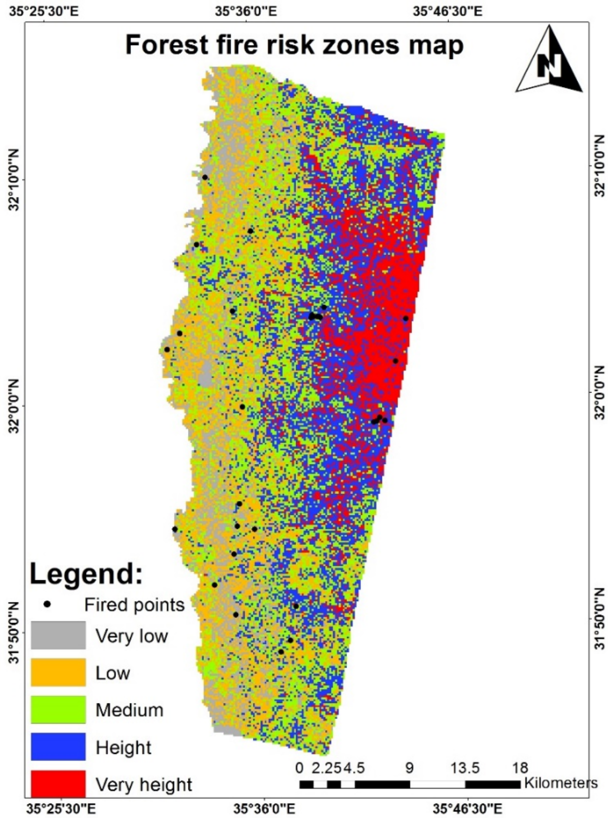

Fig. 8. Thematic map of the forest fire vulnerable zones

4. Conclusions and Recommendations

The present study is an effort to use geospatial technologies with the support of AHP and fuzzy logic to develop forest fire vulnerable maps in an area located in Jordan. The developed map has been prepared using the modified Turkish Model, where the area has been divided into five categories from very low risk area to very high. Map results showed that 39 percent of the region was labeled as high and extremely high risky zones. Maps showing the potential for forest fires were checked against available historical data. Forest fire risk zones could be assessed and specialized in order to better understand the spatial distribution of fire-prone areas. Geospatial technologies have made a significant contribution to the delivery of a highly beneficial solution for decision-makers in the future planning, prevention, and control of forest fires. This is extremely favorable since geospatial technologies have helped supply a solution.

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