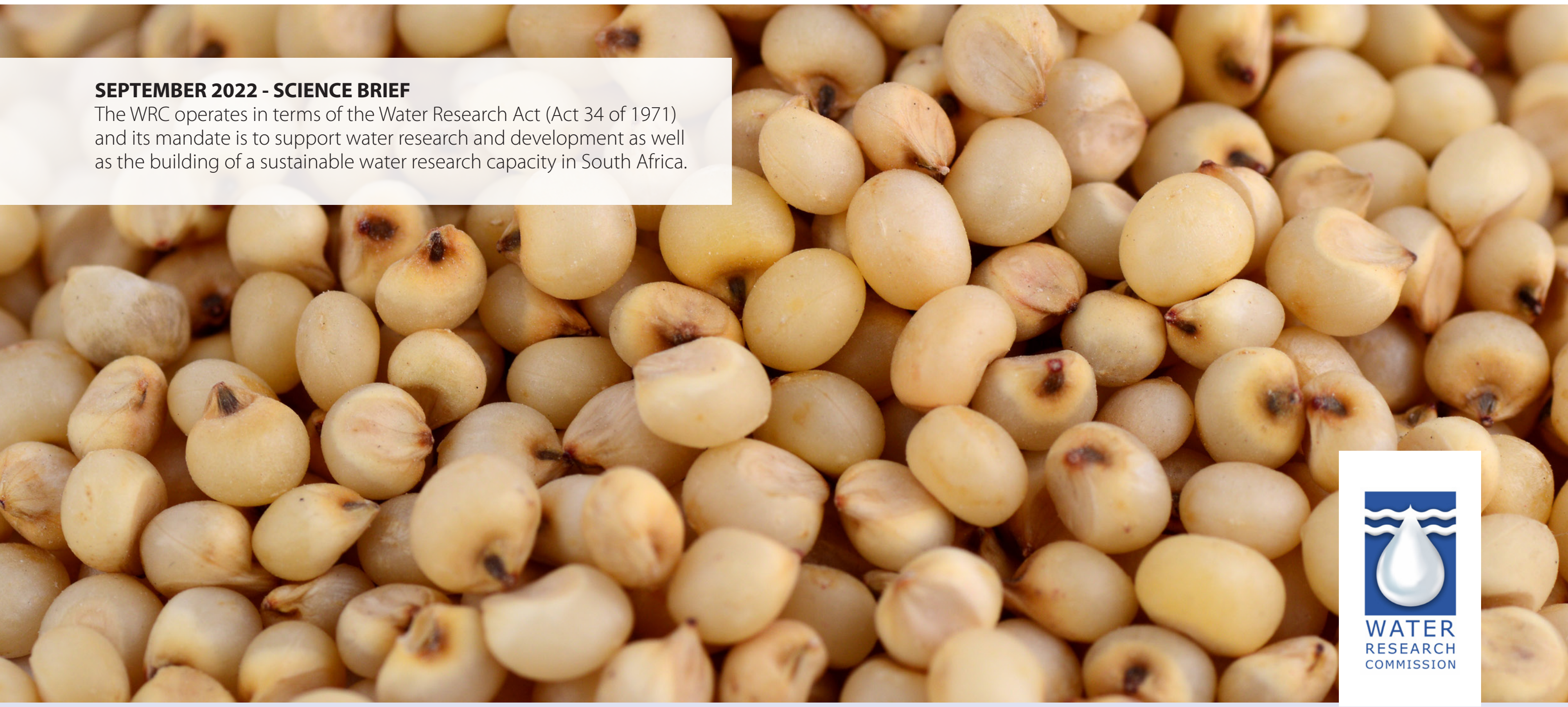

SEPTEMBER 2022 - SCIENCE BRIEF
The WRC operates in terms of the Water Research Act (Act 34 of 1971) and its mandate is to support water research and development as well as the building of a sustainable water research capacity in South Africa.

DELINEATING OPTIMAL PRODUCTION AREAS OF UNDERUTILISED INDIGENOUS CROPS AND THEIR ROLE IN CLIMATE CHANGE ADAPTATION

S. Mpandeli, S. Hlophe-Ginindza, M. Kapari and L. Nhamo

The cultivation of adapted crops such as maize and rice in southern Africa is under threat from climate change, decreasing rainfall and degraded lands. These crops are unlike underutilised indigenous crops that are uniquely suited to local environments and are more resilient to climatic variations and tolerant to local pests and diseases, adapted crops require costly inputs, agronomic practices and huge volumes of water for their production. The huge quantities of nutrients used in the cultivation of adapted crops have been a major cause of environmental degradation. Moreover, even with new seed varieties for adapted crops, food demand continues to outstrip local supply. An integrated geospatial and multi-criteria decision method (MCDM) process has been applied to delineate optimal areas suitable for cultivating Bambara groundnuts (Vigna subterannea), an indigenous underutilised crop suitable for arid and semi-arid regions in Limpopo Province, South Africa. This is an initial step to produce and mainstream underutilised indigenous crops in the main food value chain. The procedure is important for diversifying farming systems and making them more resilient (to biotic and abiotic stresses and climate change) and more successful at enhancing water, food and nutritional security. With limited water and land resources for agriculture expansion, promoting indigenous underutilised crops is a pathway to reduce water allocated to agriculture, enhance drought resilience and ensure water, food and nutrition security. Vast tracts of degraded agricultural land deemed unsuitable for adapted crops and require costly land reclamation practices can be used to cultivate underutilised crops that adapt to local extreme conditions.

Background

Underutilised indigenous crops are small and neglected crops that are not well researched and are underfunded due to their limited importance in the global food market, but are characterised by their resilience and adaptation to extreme climatic and edaphic conditions and have local significance (Mabhaudhi et al., 2019). Indigenous crop varieties are best-suited to local environmental conditions and to the needs of farmers in marginal agricultural situations (Chivenge et al., 2015). Their low input requirements give them an economic advantage over adapted crops like maize, rice and wheat (Chibarabada et al., 2017). Current changing environments in southern Africa, characterised by extreme droughts and shortened rain seasons, favour the cultivation of indigenous crops. Historically, they have always helped to ensure food and nutrition security as part of a balanced diet, when adapted crops fail, or in between harvests. They provide important vitamins, proteins and micronutrients, and can contribute to alleviating the challenges of stunting in children in developing countries (Chivenge et al., 2015). Examples of indigenous underutilised crops suitable for southern Africa are shown in Table 1.

Table 1. Examples of underutilised crops suitable for arid and semi-arid areas

	Common name	Scientific Name
Cereals	Sorghum	Sorghum bicolor
	Tef	Eragrostis tef
Legumes	Bambara groundnut	Vigna subterannea (L.)
	Lablab	Lablab purpureus (L.) Sweet
	Cowpea	Vigna unguiculata (L.) Walp
	Marama bean	Tylosema esculentum
Root and tubers	Taro	Colocasia esculenta
	Sweet potato	Ipomoea batatas
Leafy vegetables	Jews mallow	Corchorus olitorius
	Spider plant	Cleome gynandra
	Amaranth	Amaranthus sp.
	Nightshade	Solanum nigrum
	Wild watermelon	Citrullus Lanatus L.

Unlike adapted crops that require costly agronomic practices and a lot of water for their cultivation, underutilised indigenous crops are uniquely suited to local environments, are more resistant to certain climatic variations and are tolerant to local pests (Chivenge et al., 2015). Focusing on cultivating indigenous crops is, therefore, a climate change adaptation and mitigation strategy. Furthermore, the consumption of indigenous crops provides nutritional diversity for communities, is an option for crop rotation for farmers, creates niche markets in local economies, and harnesses and protects local knowledge. Underutilised crops provide further opportunities to enhance agro-biodiversity at the field level and promote nutritional diversity and disrupt pest and disease cycles and reduce the share of water allocated to agriculture. Thus, harnessing and mainstreaming local knowledge and traditional crop species as well as developing underutilised crop breeds has enormous potential to improve water, food and nutrition security

Regional and national policies in developing countries are targeting increasing the area under irrigation as a remedy to meet the food requirements of a growing population and ensure food and water security (CAADP, 2009; NDP, 2011). The increase in irrigated area targets adapted crops. Whilst such initiatives sound noble, the main challenges are water scarcity and the unavailability of land for an expanded irrigated area. In the case of South Africa, it is estimated that 98% of available water resources are already allocated with over 60% of available water resources allocated to agriculture. In southern Africa, 70% of available freshwater resources are used for agriculture and the region is already devastated by recurring droughts (Nhamo et al., 2018). Under such changing environment, more emphasis should be on producing indigenous crops at a large scale as they are suited to local harsh conditions (Mabhaudhi et al., 2016). Indigenous crops are generally acceptable to local people as they promote the preservation of culture, improve food selection and preparation concerning the needs and cultural values of local people. Identifying suitable areas for cultivating underutilised crops is the initial step for their promotion and commercialisation.

Cropland suitability mapping is an assessment of land performance when it is used to produce specific crops and it is a prerequisite to achieving optimum utilisation of the available land resources for sustainable agriculture production. Adaptation of crop growth to the capabilities and constraints of local agro-ecological conditions is a key principle of sustainable land management. Identifying optimum land for cultivating indigenous crops is important for conserving environmental resources and at the same time achieving maximum yields. Thus, cropland suitability mapping provides information for growing potential crops and deriving maximum economic benefits with lower production costs. It facilitates better water and land management. As indigenous underutilised crops are the 'future food', this study applies an integrated geospatial and multi-criteria decision method (MCDM) approach to delineate optimum areas for cultivating Bambara groundnut in Limpopo Province, South Africa.

An overview of the Bambara groundnut

The Bambara groundnut (Figure 1) is an indeterminate annual crop that grows close to the ground with seeds being produced underground (DALRRD, 2011). Being a highly adaptable legume, the Bambara groundnut is grown in diverse agroecosystems and generally grows well under drought conditions. Bambara groundnut has a low water requirement (Mabhaudhi and Modi, 2014), and has been identified as exhibiting all three categories of drought adaptation strategies which are escape, avoidance, and tolerance. However, the crop has a low tolerance for waterlogged soils and grows best in well-drained soils. Some varieties of Bambara groundnut exhibit tolerance to salinity (Mayes et al., 2019). Also, the presence of variation in photoperiod and temperature sensitivity among Bambara groundnut genotypes is a good indicator that there is room for improvement in varieties for adaptation in broad agroecological farming zones. Bambara groundnut has been identified as a potential future crop under climate change (Mabhaudhi et al., 2019). In South Africa, Bambara groundnut yield and water productivity are projected to increase by ~37.5% and 33% under climate change (Mabhaudhi et al., 2019).

Figure 1. Bambara groundnut in leaf and the seeds

The Bambara groundnut seeds are rich in carbohydrates, proteins, fibre, ash, fat, and micronutrients, making them a valuable source of nutrition for resource-poor farmers. However, limited genetic improvement, poor milling characteristics, long cooking time, and anti-nutritional factors have resulted in the crop being underutilised. Even though the crop is underutilised, the Bambara groundnut plays a key role in both foods, and cultural practices of farmers in Africa and Asia and has been integrated into intercropping systems (Mayes et al., 2019).

The methodological framework

Topography, soil properties (pH, texture, organic matter content and depth), landuse and climatic variables of rainfall and temperature are the factors that influence crop growth and thus are considered to define areas suitable for crop cultivation. Most indigenous underutilised crops in southern Africa are generally grown under rainfed or dryland conditions. The determination of weights for the factors (called criteria in suitability mapping) that influence crop growth is based on local expert knowledge and considerations from literature. Figure 2 illustrates the overall flow of the

methodology used to delineate areas suitable for crop cultivation in GIS. In GIS, the criteria layers are rasterised to facilitate the overlaying process. The Multi-Criteria Evaluation (MCE) is the basic methodology as it combines information

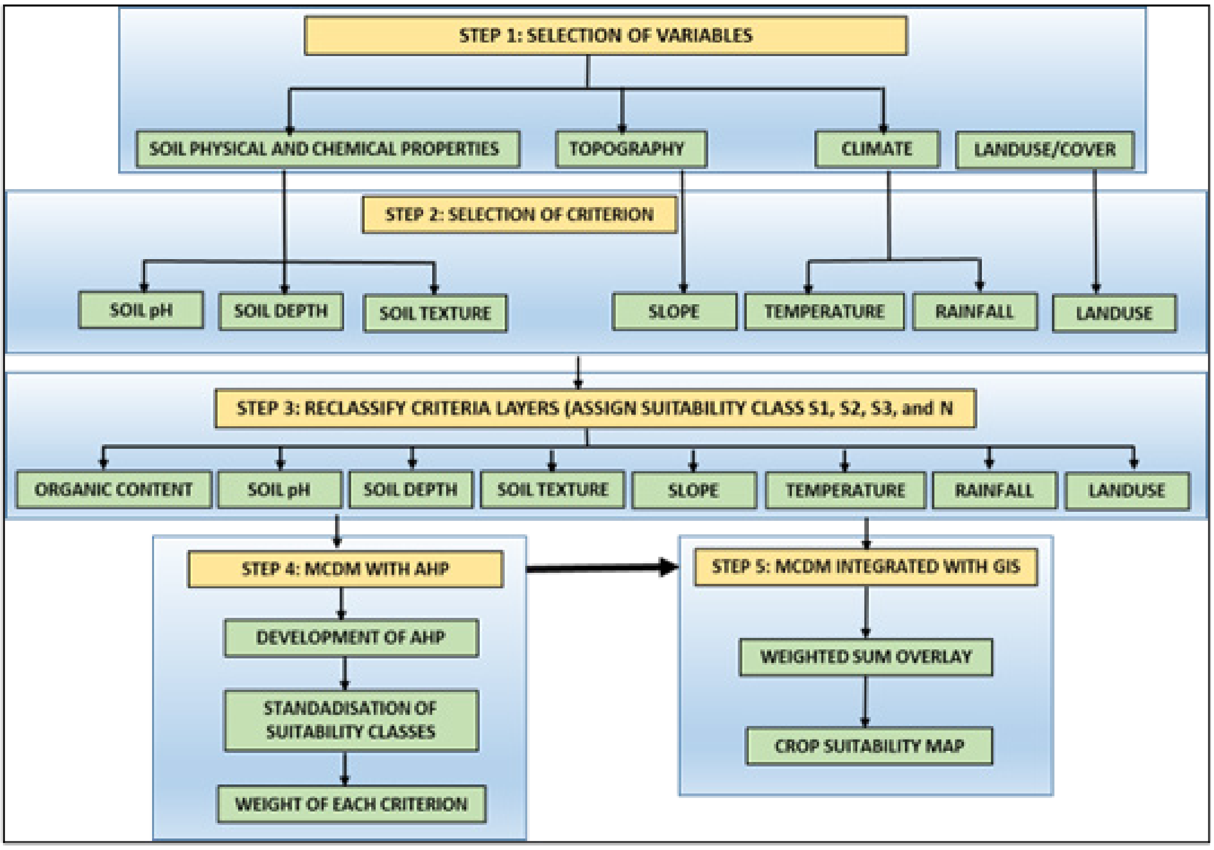

Figure 2. Methodological flowchart for crop suitability mapping.

from several criteria to produce a suitability map. The method combined with GIS produces a spatial planning tool that enables the incorporation of spatial data and value judgements into a resultant decision.

Factors required in crop suitability mapping

Topographic factor: Slope is important for site selection and analysis. Slope data, in percentage, was generated from a digital elevation model (DEM) obtained from the 30 m resolution Aster Global Digital Elevation Model (GDEM) and processed in ArcGIS's Spatial Analyst. The DEM was downloaded from the USGS's Earthdata. The lowest slope values indicate flat terrains and higher slope values indicate steeper terrains. Flat terrains are generally suitable for crop cultivation. The categorisation of slopes for crop cultivation was based on the recommendations of the Conservation of Agricultural Resources Act (CARA) as shown in Table 2.

Soil: Soil is important by providing anchorage and nutrients to plants. Soil physical and chemical properties of texture, depth and soil pH were selected as criteria in this study. Soil data were obtained from the Agriculture Research Council's (ARC) soil and Soil Soter database. Each soil thematic layer was rasterised for use in a GIS setup. Optimum soil texture, pH and depth for Bambara groundnut were obtained from the guidelines developed by DAFF as shown in Table 2.

Climate data: Rainfall and temperature are the climatic variables chosen as criteria because of their role in plant development and yield. Rainfall and temperature data were obtained from the South Africa Weather Services (SAWS). The categorisation of rainfall and temperature for Bambara groundnut was based on local crop expert knowledge and from literature and shown o Table 2.

Landuse: Current landuse determines whether a particular land can be used for agricultural purposes. In cropland suitability mapping, a landuse map is used to extract those areas that cannot be used for agriculture, for example, settlements, cultural sites and nature reserves, among others. The landuse map was derived from the 2015 Land Cover Dataset, developed by GeoTerraImage (Thompson, 2015).

Table 2. Data range and suitability classes for Bambara groundnut (*Vigna subterannea*)

Parameter	Highly suitable (S1)	Moderately suitable (S2)	Marginally suitable (S3)	Not suitable (N)
Slope (%)	0-4	4-8	8-20	>20
Rainfall (mm), Nov-Apr	550-750	450-550	350-200	>750
Av temp (oC) (Nov-Apr)	20-28	20-32	32-35	>35
Soil depth (mm)	>500	>400	>300	<300
Soil type	1, 2*, 3	4, 8, 9, 13*	6, 7, 12, 14	Other
Soil topsoil clay %	15-25	25-30	30-40	>40

The rasterised layers of the selected factors/criteria were reclassified into different suitability levels in GIS as a base to construct the criteria map for Bambara groundnut. The suitability levels for each criterion (map layers) is ranked as: Highly Suitable-S1, Moderately Suitable-S2, Marginally Suitable- S3, Not suitable-N, based on the structure of FAO land suitability classification (FAO, 1977). Table 3 shows the sources and resolutions of the datasets that were used to develop suitability levels for each criterion for Bambara groundnut. The developed raster data layers (criteria) are set to the WGS 84 Web Mercator coordinate system and resampled to 30 m spatial resolution

Table 3. Cropland suitability mapping datasets, source and resolution

Dataset	Data source	Resolution/Scale
Rainfall and temperature	SA Weather Services	30m
Soil properties	ARC and Soter soils databases	30m
Slopes	Aster GDEM	30m
Landuse	GeoTerraImage	30m

The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), a multi-criteria decision method approach (MCDM), and the pairwise comparison matrix (PCM) were used to assign weights to each criterion as proposed by Saaty (Saaty, 1987). In a PCM, factor weights are determined by comparing two factors together at a time. The values of the pairwise comparisons in the AHP are determined according to Saaty's scale: [9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9] (Saaty, 1977) (Table 5). The relative relevance of one criterion over another is taken into account while making comparisons using this approach. A rating of 9 indicates that in relation to the column factor, the row factor is extremely important. On the other hand, a rating of 1/9 indicates that relative to the column factor, the row factor is extremely less important. In cases where the column and row factors are equally important, they have a rating value of 1 (table 4).

Table 4: Saaty's scale for weight assignment.

Less Important					More Important			
Extremely	Very Strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very Strongly	Extremely
1/9	1/7	1/5	1/3	1	3	5	7	9

Through the PCM, the AHP calculates the weighting for each criterion (*wi*) by taking the Eigenvector corresponding to the largest Eigen value of the matrix, and then normalising the sum of the components to unity as

$$\sum_{i=1}^{n} = wi = 1 \quad [1]$$

The overall importance of each of the individual criteria is then determined. The basic input is the pairwise matrix, A, of n criteria, established based on Saaty's scaling ratios, which is of the order (n x n) as defined in Equation 2.

$$A = [aij], i, j = 1,2,3 \ldots n \quad [2]$$

Where A is a matrix with elements ***aij***. The matrix generally has the property of reciprocity, expressed mathematically as:

$$aij = \frac{1}{aji} \quad [3]$$

After generating this matrix, it is then normalized as a matrix B

$$B = [Bij], i, j = 1,2,3 \ldots n \quad [4]$$

In which B is the normalized matrix of A (Table 4), with elements ***bij*** defined as:

$$bij = \frac{aij}{\sum_{i=}^{n} aij = 1,2,3 \ldots, n} \quad [5]$$

Each weight value ***wi*** is computed as:

$$wi = \frac{\sum_{j=1}^{n} bij}{\sum_{i=1}^{n} \sum_{j=}^{n} bij}, i, j = 1,2,3 \ldots, n \quad [6]$$

Criteria standardisation

Criteria layers (maps) are presented in ordinal classes (S1, S2, S3 and N), representing the degree of suitability of one attribute class from the other based on the optimal requirements for the growth of the crop. Prior to being weighted and aggregated, criteria are measured on different scales and standardized. Each class is rated according to how important class S1 is with respect to a particular criterion to contribute to the final goal. The importance of one class is compared to the other within a single criterion or factor. The maximum Eigenvectors approach of 0 to 1 scale was applied to standardise the factor layers. In the case of the ideal mode, AHP the columns of the decision matrix in the original AHP are normalized dividing by the largest entry in each column. A PCM was used to rate and standardise the ordinal values.

Consistency ratio

In the application of the AHP method, the weights derived from a PCM should always be consistent at an acceptable ratio. The consistency ratio (CR) indicates the likelihood that the matrix judgments were generated randomly and are consistent. CR indicates the amount of allowed inconsistency (0.10 or 10%). CR values higher than 0.1 indicate that the comparisons are less consistent, while smaller values indicate that comparisons are more consistent. When CRs are above 0.1, the pair-wise comparison is not consistent and should be re-evaluated (Saaty, 1977). The CR is calculated as:

$$CR = \frac{CI}{RI} \quad [7]$$

where, CR is consistency ration, CI is consistence index and RI is the random index, the average of the resulting consistency index depending on the order of the matrix given by Saaty (Saaty, 1977). CI is calculated as:

$$CI = \gamma - \frac{n}{n-1} \quad [8]$$

where, γ is the maximum Eigen value, and n is the number of criteria or sub-criteria in each pairwise comparison matrix.

Pairwise matrix comparison for Bambara groundnut

The PCM for Bambara groundnut is given in Table 4. The diagonal elements are the values of unity (i.e., when a factor is compared with itself the relationship is 1). Since the matrix is also symmetrical, only the lower half of the triangle is filled in and the remaining cells are reciprocals of the lower triangle. The normalisation of the PCM is shown in Table 5 where the weight of each criterion is determined using Equations 5 and 6, respectively. The sum of weights should always be 1. The CR for the pairwise matrix for Bambara groundnut is 0.09 which is within the acceptable range.

Table 5. Normalised pairwise comparison matrix and computation of criterion matrix

Criteria	Normalised pairwise comparison matrix								
	Slope	Soil depth	Temp	Rainfall	pH	Texture	Landuse	Weight	Rank
Slope	0.0857	0.1429	0.1056	0.0549	0.1579	0.0303	0.1429	0.1029	3
Soil depth	0.0285	0.0476	0.0454	0.0330	0.0526	0.0303	0.1429	0.0543	1
Temp	0.2572	0.3333	0.3173	0.4946	0.3684	0.4546	0.1429	0.3383	7
Rainfall	0.2572	0.2381	0.1056	0.1649	0.2632	0.2728	0.1429	0.2064	6
pH	0.0285	0.0476	0.0454	0.0330	0.0526	0.0303	0.1429	0.0543	2
Texture	0.2572	0.1429	0.0635	0.0549	0.0526	0.0909	0.1429	0.1150	4
Landuse	0.0857	0.0476	0.3173	0.1649	0.0526	0.0909	0.1429	0.1288	5
CR = 0.09								Σ = 1	

Conclusions

By using available natural resource information and matching it to specific crop production requirements, the basic principles of "matching" used in the land evaluation process are followed. The example used here of Bambara groundnuts can be compared with other similar crops, in association with yield estimates and enterprise budgets, to evaluate the suitability empirically for a range of underutilised crops in any specific area. Further to this, and due to the minimum data set required, the method can be replicated across South Africa and the region to assess underutilised crops' suitability. Growing Bambara groundnut with the appropriate management options can be used as an adaptation strategy in areas classified as moderately suitable and marginal. It is imperative to accompany the information regarding land suitability with transformative and autonomous adaptation strategies to mitigate climate risks. In cases where resources are limited, the adoption of multi-cropping and rainwater harvesting, and soil conservation techniques can be used. This is particularly important for resource-poor farmers who reside in many of the marginal areas identified. To smallholder farmers, NUS can address several socio-economic related challenges; therefore, future studies should consider factors such as access to markets, proximity to roads and population density.

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