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INTEGRATION OF AGRO-ECOLOGICAL AND GROUNDWATER RESOURCES FOR THE ASSESSMENT OF CROP SUITABILITY POTENTIAL MODELING: THE CASE OF LIMPOPO PROVINCE, SOUTH AFRICA

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ABSTRACT
A comprehensive subtropical fruit potential model (IUM) was established through novel integration of groundwater resources with multi-criterion predictive parameters. Equal-weights overlay was applied to reclassified and ranked rasters to institute IUM. Avocado and litchi had the least spatial extent that concealed the micro-climatic zones of high rainfall (>1000 mmpa) in Vhembe, Mopane, and Waterberg districts; meanwhile, mango and citrus were the crops with the most extensive province-wide distribution. Subsequent potential was apportioned in these sequences by constituency: Waterberg (1719019 ha), Mopane (977741 ha), Vhembe (764044 ha), Capricorn (579506 ha), and Sekhukhune (379968 ha). The IUM resulted in the demarcation of 8.7 million ha to produce the selected crops, which reflected an increase of 7.7 million from the rainfed suitability model. The integrated model would result in the creation of 10.87 million direct employments. The IUM expanded the agrarian sector with positive spinoffs for agribusiness development.

Contribution/Originality: This study uses new estimation methodology that integrates rainfed and groundwater resources with agro-ecological and climatic predictive parameters. This study introduces a new formula to establish a novel linear regression model for the simulation of subtropical crop suitability based on the integrated water resources of an area.

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1. INTRODUCTION

Crop suitability qualitatively evaluates the congruence between crop requirements and the prevalent geo-climatological conditions (He, Yao, Chen, & Ongaro, 2011; Mu, 2006; Prakash, 2003). The process used to define suitability involves the analysis and integration of the predictive determinants and interpretation of the subsequent land performance model (He et al., 2011; Mu, 2006; Prakash, 2003). The primary mandate for this exercise is the appraisal of the indexed potential model that defines how well a piece of land is capable of supporting specific crops (Pan & Pan, 2012). The concept of crop suitability was introduced during the mid-late 20th century with the notion to delineate appropriate land for specific agricultural commodities (FAO, 1976; FAO, 1983; FAO, 2007). This initiative was directed towards curbing the environmental degradation that follows agricultural malpractices and overexploitation of resources associated with rapid population growth (Elsheikh et al., 2013).

Rapid population growth leads to inadequate access to food. According to the FAO, IFAD, and WFP (2015), approximately 800 million people around the world do not have access to sufficient food, of whom 25% are children under the age of 5 years.

The Food and Agriculture Organization of the United Nation (FAO, 2018) expects this proportion to increase, particularly in the developing part of sub-Saharan Africa. Fortunately, the crop suitability model represents a key spatial planning tool with the potential to delineate prospective areas for generation of additional food resources.

According to Elsheikh et al. (2013), agricultural production should be preceded by crop suitability assessment, to provide assurance that prospective environmental degradation likely to be imposed on the environment through improper crop production is marginalized (Bodaghabadi, Faskhodi, Salehi, Hosseinifard, & Heydari, 2019; De la Rosa, Mayol, Diaz-Pereira, & Fernandez, 2004; Halder, 2013). Such an assessment also represents a key role for governments, private companies, and financial institutions to mitigate the risks associated with investment in the agrarian sector (Monjurul, Ahamed, & Noguchi, 2018). Crop suitability modeling was derived from soil type mapping, with the mandate to generate potential agricultural areas Bodaghabadi et al. (2019).

Thereafter, FAO (1976) set out a systematic framework for land evaluation for rainfed and irrigated agriculture. Then, FAO (1996) established crucial parameters for the prediction of the crop suitability incorporating climate, soil type, and landform.

These contributions established a fundamental layout for the emergence of multi-criterion linear regression modeling that involves the Geographical Information System (GIS), which has since become a standardized approach in crop suitability assessment (Chandio, Matori, Lawal, & Sabri, 2011; Muhsin, Ahamed, & Noguchi, 2017; Rikalovic, Cosic, & Lazarevic, 2014). Conventional GIS based modeling includes Boolean conditional mapping, satellite imagery (Malczewski, 2006; Petja, Nesamvuni, & Nkoana, 2014), and land capability mapping (Baniya, 2008). Over time, these techniques have advanced significantly to incorporate complex multi-criterion methods (Behrens, Schmidt, Zhu, & Scholten, 2010; Nabiollahi, Golmohamadi, Taghizadeh-Mehrjardi, Kerry, & Davari, 2018; Nabiollahi, Eskandari, Taghizadeh-Mehrjardi, Kerry, & Triantafilis, 2019; Pahlavan-Rad et al., 2014) that include linear combination, simple limitation, fuzzy-logic modeling, artificial neural networks, and the analytical hierarchy rocess (AHP) (Ozdemir, 2020).

The prominence of GIS-based systems in the simulation of crop potential is attributed to their simplicity and the ability of the technology to integrate different datasets (Dengiz, Özyazici, & Sağlam, 2015). One major drawback, however, is the inclusion of groundwater resources for crop prediction.

This limitation renders these systems less than ideal for application in typical arid and semi-arid regions, particularly in Limpopo Province, South Africa (Ndwambi, Nesamvuni, Mpandeli, Tshikolomo, & Van Niekerk, 2020), which is in the subtropical region (Mpandeli & Maponya, 2014). Based on its location, the province has the potential for subtropical fruit production (Tshikudu, 2005) but the potentiality is curbed due to the impact of climate change (Chikosi, Mugambiwa, Tirivangasi, & Rankoana, 2018).

As a result of climate change, rainfall has declined and rainy days have now become too short and sporadic – to an insignificant level – to be able to meet agricultural needs, and surface water resource s are almost entirely allocated (Chikosi et al., 2018; Mpandeli & Maponya, 2014). Therefore, this study was conducted to establish a novel linear regression model for the simulation of subtropical crop suitability potential based on the integration of rainfed irrigation and groundwater resources with agro-ecological and climatological predictive parameters. This improved potential will aid in the generation of additional food resources and the development of smallholder farming and agribusiness.

2. MATERIALS AND METHODS

2.1. Study Area

2.1.1. Geographical Setting

The study was conducted in Limpopo Province, which is one of nine provinces constituting the Republic of South Africa. It is positioned towards the northwestern part of the country. The locality shares international borders with three of the four neighboring countries, namely, Botswana, Zimbabwe, and Mozambique. The locality map in Figure 1 indicates that the area lies between 26° and 32° east, and 22° 10′ and 25° 20′ south and has a land area of 125 754 km^2. Limpopo Province has a population of about 5.7 million, with the highest proportion (75%) residing in the rural settings (villages and informal settlements) (Statistics South Africa, 2015).

2.1.2. Agricultural Contribution

Limpopo Province is often referred to as the bread and fruit basket of South African as it accounts for at least 60% of all the fruit, vegetables, maize meal, wheat, and cotton produced in the country. According to World Travel Information, the province possesses some of the richest agricultural areas in the country. Furthermore, the province receives over 45% of the R2 billion annual turnover of the Johannesburg Fresh Produce Market. According to Statistics South Africa (2019), Limpopo Province is the most food-secure region in South Africa, with 93% of the inhabitants having adequate access to food resources.

Limpopo Province is a subtropical region (Mpandeli & Maponya, 2014). These regions are renowned for possessing exceptional potential for subtropical fruit production (Tshikudu, 2005), and hence there is a high level of participation in agricultural production by its inhabitants. The agricultural sector in the province comprises both smallholder and commercial farmers. The central government, together with the provincial arm, has identified the smallholder sector as a primary tool for economic reform and job creation through the promotion of this sector to the mainstream economy.

2.1.3. Climatic Setting

The climatic setting of the area ranges from dry sub-humid to semi-arid, attributed to wet, hot summers and dry, cold winters (Kabanda, 2004). The mean annual temperature ranges between 18 and 30°C (Mpandeli, 2006; Mpandeli & Maponya, 2014; Naledzani, 1999). Rainfall trends decrease from the east (>1000 mmpa) to the west (<400 mmpa). The effect and impacts of climate change are experienced considerably in the agricultural industry. After the impact of climate change, semi-arid is defined by insignificant and unreliable precipitation (Mpandeli & Maponya, 2014; Ntikinca, 1999). Despite this, the province is experiencing significant population growth that is overstretching current water resources. Hence, there are growing concerns as to how the agrarian sector should be sustained to meet needs at both provincial and national levels.

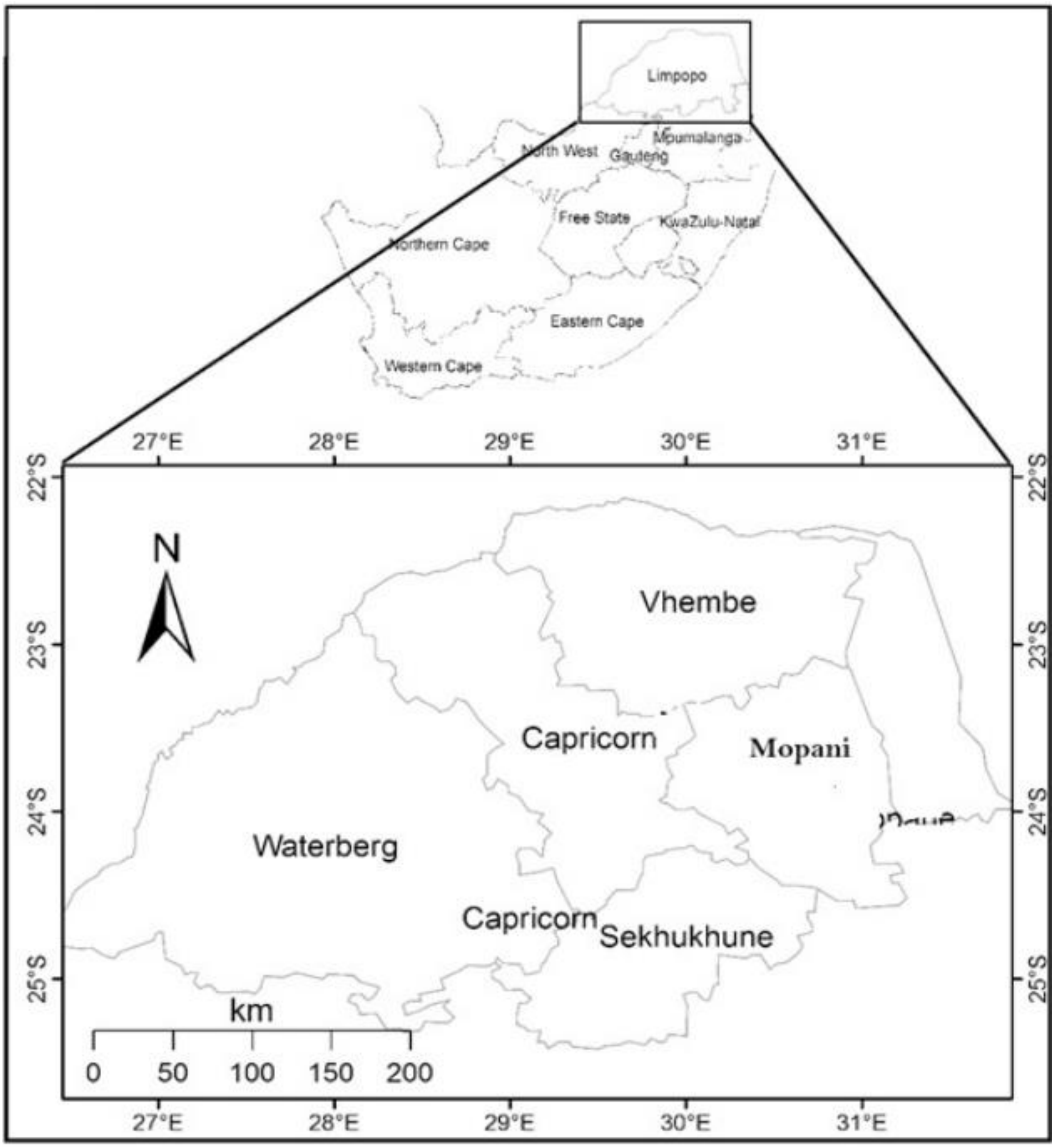

Figure-1. Locality map showing the geographic coordinates of Limpopo Province (Ndwambi et al., 2020).

2.1.4. The Novel Subtropical Fruit Suitability Model

This section presents the methodology that was employed for the establishment of the novel linear regression subtropical fruit (avocado, citrus, mango, and litchi) suitability model for Limpopo Province. The suitability model was based on auxiliary datasets obtained from ARC-ISCW (2016)m which is a subsidiary of the Water Research Commission (WRC) of the Republic of South Africa. This subsection also describes the data quality assurance and processing techniques that were employed to establish the crop suitability model.

2.1.5. Production Requirements of Subtropical Fruit

The crop suitability modeling was achieved through matching subtropical crop requirements to the prevalent agro-ecological, climatological, and available water resource for irrigation (rainfed and groundwater resource). Subtropical crop requirements were appraised exclusively from ARC-ISCW (2016). The optimal requirements for citrus incorporate the absence of frost, the minimum temperatures in winter should be ≥3°C while the maximum for the same period should be ≤13 °C. This crop flourishes within a narrow spectrum of slightly acidic pH (6.0–6.5. Ideal soil for this commodity should be well aerated, with depth ranging from 1 to 2 m, and clay composition of 10–40%.

Avocado relishes a humid environment with exceptional high precipitation in excess of 1000 mmpa. It requires cold temperatures and can cope well at <0°C, but begins to fade once temperatures exceed 25°C. Avocado thrives in areas with a mean annual temperature of 20–25°C. Optimal soil physiochemical attributes are 600 mm depth, clay composition of 20–40%, and slightly acidic pH (5.0–7.0). Litchi and the mango generally favor warmer temperatures; they can only endure winter temperatures >6 and 5°C, respectively. Furthermore, these crops are suitable for a diverse array of soil types. Mango is one of the most drought-resistant crops and can withstand temperatures >40°C. It can also perform well in a drier environment with rainfall of <400 mm. However, elevation should not exceed 1200 masl. Furthermore, the crop is suitable for a diverse array of soil types whereas litchi require soil depth of at least 1000 mm.

2.1.6. Crop Suitability Requirements (ARC-ISCW, 2016; ARC-ITSC, 2003)

Citrus Optimal Potential: '{Min Avg Temp July} >= 3˚C and {Min Avg Temp June, July, Aug} <= 13 3˚C; and {Effective Soil Depth} >= 100 cm; and {Avg Clay %} >= 15 and <= 35; and {Soil form} <> "Va" and Precipitation + groundwater>=1000mm

Citrus Suitable Potential: '{Min Avg Temp July} >= 3˚C; and {Min Avg Temp June, July, Aug} <= 13 ˚C; and {Effective Soil Depth} >= 90 cm and < 100 cm; and {Avg Clay %} >= 15 and <= 35; Or and {Effective Soil Depth} >= 100 cm; and {Avg Clay %} > 5 and < 15 and > 35 and < 50; and {Soil form} <> "Va, Rg, Wo, Ar".

Avocado Optimal Potential: '{Mean Annual Temp} >= 20 ˚C and <= 25 ˚C; and {Mean Annual Precipitation + groundwater} >= 1000 mm; and {Mean Annual Temp, Oct-Nov} >= 15oC; and {Effective Soil Depth} > 600 mm; and {Avg Clay %} < 50'.

Avocado Suitable Potential: '{Mean Annual Temp} >= 20 ˚C and <= 27 ˚C; and {Mean Annual Precipitation + groundwater} >= 800 mm; and {Mean Annual Temp, Oct-Nov} >= 15 ˚C; and {Effective Soil Depth} > 600 mm'.

Mango Optimal Potential: '{Avg Monthly Temp, May, Jun, Jul, Aug} > 5 ˚C; and {Mean Annual Max Temp} >= 27 ˚C and <= 36 ˚C; and {MMR Sept} <= 50 and {MMR Oct} <= 85 and {MMR Nov} < 110 and {MMR Dec} < 140 and {MMR Jan} < 140 and {MMR Feb} < 140; and {Altitude} < 1200 m.a.s.l; and {Effective Soil Depth} >= 75 cm; [vi] {Avg Clay %} <= 15 and <= 25; [vii] {Soil form} <> "Bo, Ar".

Mango Suitable Potential: '{Avg Monthly Temp, May, Jun, Jul, Aug} > 5 ˚C; and {Mean Annual Max Temp} >= 27 ˚C and <= 36 ˚C; and {MMR Sept} <= 50 and {MMR Oct} <= 85 and {MMR Nov} < 110 and {MMR Dec} < 140 and {MMR Jan} < 140 and {MMR Feb} < 140; and {Altitude} < 1200 m.a.s.l; and {Effective Soil Depth} >= 60 cm and < 75 cm; [vi] {Avg Clay %} <= 15 and <= 25; Or and {Effective Soil Depth} >= 75 cm; and {Avg Clay %} (>= 10 and < 15) and (>25 and <= 50); [vii] {Soil form} <> "Bo, Ar".

Litchi Optimal Potential: '{Mean Annual Temp} >= 16 ˚C and <= 25 ˚C; and {Altitude} <= 640 m.a.s.l; and {Effective Soil Depth} >= 100 cm; and {Avg Clay %} >= 10 and <= 45.

Suitable Potential for Litchi: {Mean Annual Temp} >= 16 ˚C and <= 25 ˚C; and {Altitude} <= 640 m.a.m.s.l; and {Effective Soil Depth} >= 90 and < 100 cm; and {Avg Clay %} >= 10 and <= 45.

2.2. Data Processing

This section presents the data processing techniques adopted for establishment of the comprehensive crop suitability model. Carl (1996) defined data processing as a process of collection and manipulation of raw data to yield meaningful information. A file Geo-database was prepared in the ArcGIS environment to enable data processing. All datasets were transformed into the WGS84 coordinates system using the georeferencing tool in ArcGIS software. The mandate for this was to simplify the process of data extraction only for areas that coincide with Limpopo Province to enable temporal data processing and reduction of data redundancy. Quality assurance was performed through a spatial dimension comparison of the features on different data. Where there was a need, the extent of the features was modified based on size as reflected on the orthophoto.

2.3. Integration of Rainfall and Groundwater Resource

Predictive parameters of suitability modeling were converted to spatial resolution of 500 m, to ensure that the resultant model would yield meaningful results. The climatological component (rainfall) was integrated into the groundwater resource, performed on a locality basis. Since crop water requirements are expressed in terms of rainfall (mmpa) and annually sustainable groundwater resource is expressed in mm³/km², the latter was converted to mmpa and the modeling was performed with groundwater abstraction restricted to 60% to accommodate other users. The two water-based units (rainfall and groundwater) were incorporated to give spatial water resource quantity.

The predictive parameters were reclassified into three categories. The prime value of four was apportioned to the portion of the attributes corresponding to the optimal crop requirement, while three was allotted to the marginal suitability area. At the other end of the spectrum, zero was allocated to those attributes that neither support nor hinder crop potential. Reclassification was repeated for all input parameters for the selected crops. The predictive parameters were assigned equal weights such that their sum was equal to 1. Equal weights were opted for to nullify the biases associated with the operator's preference towards specific layers. Furthermore, this weighting also yields the delineation of absolute potentiality, instead of propelling areas that are not ideal to optimal classes based on highly weighted parameters. These layers were incorporated into the crop suitability model using Equation 1:

$$_{u}\,Cp = \sum_{j}^{i} wi.j \qquad (1)$$

Where *Cp* is crop potential and *wi* is the reclassified thematic layer.

Since equal weighting was adopted for the integrated potential assessment, the optimal potential was attributed to the mean index of 4, and the suitable potential with the mean index value equal to or greater than 3 but less than 4.

3. RESULTS AND DISCUSSION

This section presents the results of the novelty methodology that was employed to develop the linear regression suitability of the selected crops (avocado, citrus, mango, and litchi) through integration of the reclassified maps of the agro-ecological, climatological, and groundwater resources. The prospective areas for each of the selected crops were categorized into the optimal and suitable (marginal) areas. This potentiality constitutes a fundamental prerequisite for the developmental purposes of the agri-business and projection of smallholder farmers into the mainstream economy.

3.1. Spatial Extent of Subtropical Fruit Suitability Categories

The subtropical fruit suitability modeling resulted in two prospective categories, namely the optimal potential area and the suitable (marginal) potential area. The two prospective potentials are shown in Tables 1 and 2, respectively.

Table-1. Spatial comparison of the RFM and the UGM novel models in terms of the extent of the optimal potential area for selected crops.

Distric	Avocado (ha)		Citrus (ha)		Mango (ha)		Litchi (ha)	
	RFM[1]	IUM[2]	RFM	IUM	RFM	IUM	RFM	IUM
Capricorn	1160	36628	55264	282914	17762	235083	193	24881
Mopane	13705	86219	34093	464953	18722	182820	16902	243749
Sekhukhune	294	6740	30836	182163	37063	149485	2550	41580
Vhembe	3551	68943	37999	283835	32948	238553	20305	172713
Waterberg	0	260207	55850	556009	12350	892556	0	10247
Total	18 710	458737	214042	1767874	118845	1698497	39950	493170
[3]Increase		440027		1553832		1579652		453220

Note: [1]RFM = Geographical Information System-based crop suitability model (rainfed water resources).
[2]IUM = Integrated Geographical Information System-based crop suitability model (rainfed and underground water resources).
[3]Increase = increase in total optimum potential area (ha) when IUM is used.

Tables 1 and 2 reflect the spatial extent corresponding to each category in each of the five district municipalities constituting Limpopo Province. As indicated in Table 1, there was an increase in toptimum potential area (ha) for all commodities when the IUM (Integrated Geographical Information System-based crop suitability model – Rainfed & Underground water resources) was used. This increase was highest for mango (1,579,652 ha), followed by citrus (1,553,832 ha), litchi (453,220 ha), and avocado (440,027 ha). Within commodities there were clear district-level increases that could benefit SHAE expansion if resources are provided for commodity-based production approach.

For avocado the highest increase in the potential areas using IUM was in Waterberg District, with an increase of 56.72%, followed by Mopani at 18.79%.

The same trend was with evident for citrus in Waterberg, with a 31.45% increase and Mopani with 26.30%. Mango as a commodity showed the highest increase in Vhembe, with 14.04% followed by Capricorn at 13.84%. Litchi was more skewed to the northeast of the province, with the highest increases in Vhembe (35.02%) and Mopane (49.43%). The potentiality is in accordance with Mahmudul, Toriman, Chamhuri, and Basri (2011), that crop production is highly influenced by rainfall trend. Similarly, Table 2 shows that there was an increase in the suitable potential area (ha) for all commodities when the IUM was used.

The highest increase in suitable potential for all commodities was for mango (4,743,021 ha), followed by avocado (1.598,229 ha), litchi (1,234,819 ha) and citrus (1,155,316 ha). For avocado, Waterberg and Mopani followed the trend reported in Table 1 under the optimum potential, with increases of 41.76% and 24.50%, respectively. For citrus the increase was highest in Vhembe at 42.71%, followed by Waterberg with 23.00%. Mango was highest in Waterberg and Vhembe, with increases of 31.12% and 28.17%, respectively. For litchi the highest increase was in Waterberg and Mopani, at 33.15% and 27.28%, respectively.

Table-2. Spatial comparison of the RFM and the UGM novel models in terms of the extent of the suitable potential area for selected crops.

District Name	Avocado (ha)		Citrus (ha)		Mango (ha)		Litchi (ha)	
	RFM	IUM	RFM	IUM	RFM	IUM	RFM	IUM
Capricorn	784	90957	23393	624294	54840	681869	98	131408
Mopane	22136	400477	0	335941	59342	1038216	0	357521
Sekhukhune	0	251897	63105	90795	49169	320011	687	117103
Vhembe	12862	208312	33315	74247	71259	1412596	74621	270156
Waterberg	0	682368	186329	336181	35444	1560383	403	434440
Total	35782	1634011	306142	1461458	270054	5013075	75809	1310628
Increase	0	1598229	0	1155316	0	4743021	0	1234819

[1]RFM = Geographical Information System based crop suitability model (eainfed water resources).
[2]IUM = Integrated Geographical Information System based crop suitability model (rainfed and underground water resources) .
[3]Increase = increase in total suitable potential area (ha) when IUM is used.

The map in Figure 2 portrays the spatial extent and distribution of the optimal (gray) and marginal (yellow) potential areas for avocado in Limpopo Province. According to this map, the optimal potential areas are spatially restricted to the eastern margin of the province that constitutes Vhembe, which coincides with Thulamela and Makhado, as well as Mopane (Greater Letaba and Greater Tzaneen). This potentiality was corroborated by Mpandeli and Maponya (2014), with their assertion that there is a micro-climate with precipitation >1000 mmpa in Tshakhuma, Tshiombo, and Tzaneen that coincides with the reflected potential. The rainfed potential model that was established by Ndwambi et al. (2020) indicated Vhembe and Mopane as the best regions for avocado, at12,862 ha and 22,136 ha, respectively. However, re-evaluation incorporating the groundwater resource in Table 2 yielded a spatial extent of 208,312 ha and 400,477 ha, respectively. The follow-up study depicted significant expansion on the extent of the potential in the two districts, at 195,450 ha and 378,341 ha.

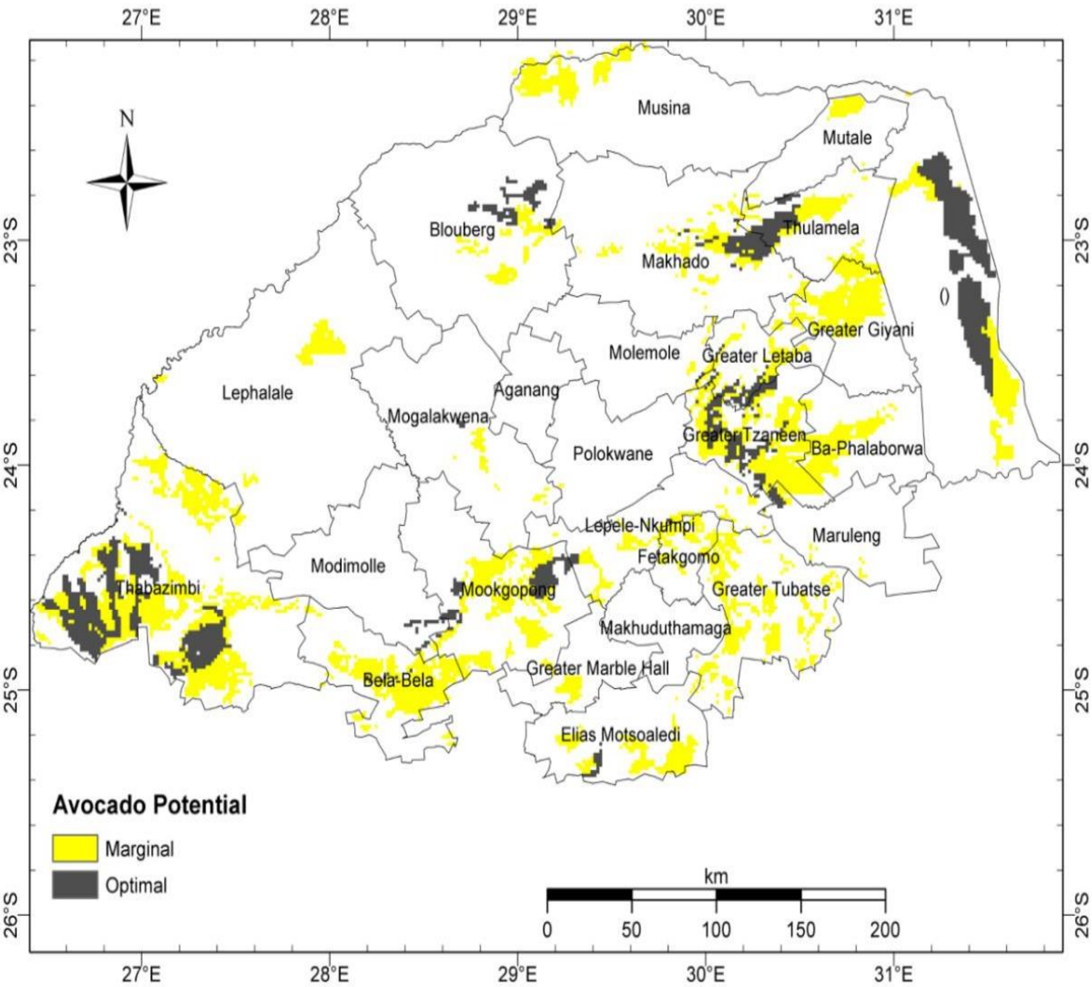

Figure-2. A map showing the extent and the distribution of the optimal and the extent of the avocado potential.

Contrary to the rainfed potential, the western side of the study area also reflects the optimal potential that conforms with Blouberg, Mookgopong, and Thabazimbi. Despite the area having low rainfall of about 400 mmpa, which is insufficient for avocado cultivation, the section exhibits good potential for this water-demanding crop. Nonetheless, this potentiality may be interpreted in terms of the groundwater levels for which the area is renowned. Ultimately, this subsurface resources significantly improve the potential for this subtropical fruit. Figure 3 shows a map reflecting the suitable and the optimal potential of citrus.

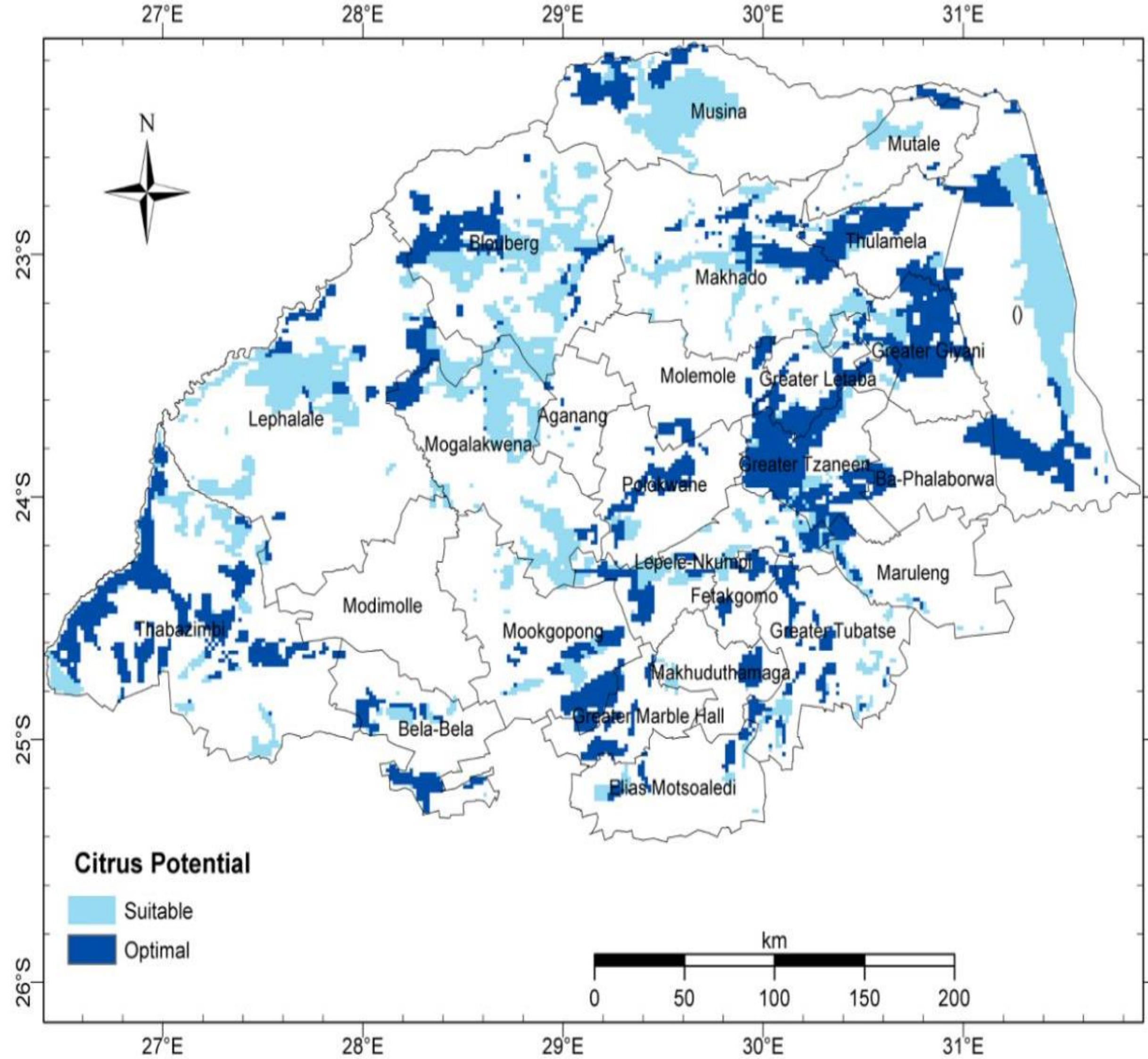

Figure-3. Map reflecting the suitable and the optimal potential of the citrus.

According to Table 2, the spatial distribution of citrus under optimal potential in Limpopo Province is as follows: Capricorn (624,294 ha), Mopane (335,941 ha), Sekhukhune (90,795 ha), Vhembe (74,247 ha), and Waterberg (336,181 ha). Meanwhile, the citrus potential map in Figure 3 indicates the spatiality of citrus throughout Limpopo Province. According to Figure 3, citrus shows a similar spatial trend to avocado. The prospective areas are prominent to the east but decline with westward progression. The significant spatial extent to the east is in Vhembe (Makhado and Thulamela), Mopane District (Greater Giyani, Greater Letaba, and Greater Tzaneen), Capricorn (Blouberg and Polokwane), and Sekhukhune (Fetakgomo, Greater Marble Hall, Fetakgomo, and Mogkopong).

There are also prominence occurrences stretching along the Limpopo River flanking Limpopo Province in Musina, Blouberg, and Lephalale, stretching to Thabazimbi and Bela-Bela. In a similar fashion to avocado, the novel citrus model exhibits significant improvement in rainfed potential established by Ndwambi et al. (2020). The incorporation of groundwater resources for the prediction of the ideal prospective area led to the expansion of this category by 1,155,316 ha throughout the province (Table 2). Figure 4 demonstrate the marginal and optimal potential distribution of mango in Limpopo.

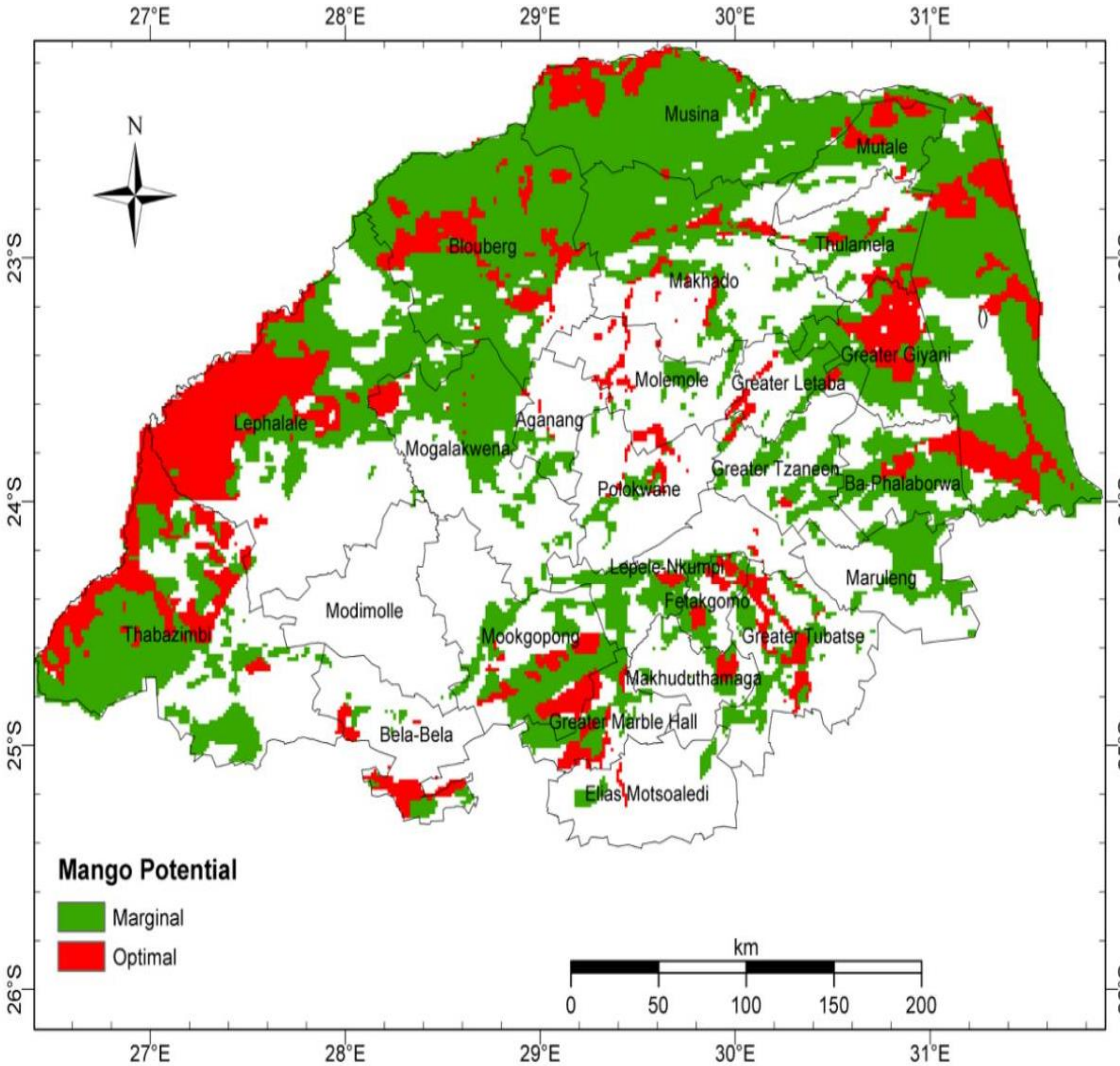

Figure-4. Map of the marginal and optimal potential distribution of mango in Limpopo.

According to ARC-ITSC (2003), mango is the least demanding crop in terms of agro-ecological requirements. It is in this regard that this crop portrays the greatest spatial potential area in the province. Table 2 shows the spatial distribution of mango: Capricorn at 235,083 ha, Mopane at 182,820 ha, Sekhukhune at 149,485 ha, Vhembe at 238,553 ha, and Waterberg at 892,556 ha.

Contrary to the potentiality of avocado and citrus, for mango (Figure 4) potentiality increased according to westward progression. The lesser potentiality in the east is attributed to high precipitation. According to ARC-ITSC (2003), mango thrives in a rainfall range of 400–600 mmpa. Besides, this crop requires relatively warmer temperatures, such conditions being more prevalent in the west: the west constitutes the highest spatiality for mango in the province. This potential is a result of the warmer temperatures that the area experiences, and sufficient water resources (both surface and groundwater). The incorporation of groundwater for the establishment of the mango suitability resulted in the spatial expansion of 1,579,602 ha from the rainfed suitability model of Ndwambi et al. (2020). The greater part of the area within this category comprises Mutale, Musina, Lephalale, and Blouberg. The spatial distribution and variability of litchi are shown in Figure 5.

This map shows that the potential of this area is restricted to the east of Limpopo Province. The areas within this category include Vhembe (Makhado, Mutale, and Musina) and Mopane (Greater Letaba and Tzaneen). The former accounts for 172,713 ha and the latter for 243,749 ha. Spatial restriction for litchi is attributed to the low mean annual rainfall that the majority of the province receives. Meanwhile, the optimal zones coincide with the microclimate zones that experience significant precipitation (>1000 mmpa). According to ARC-ISCW (2016), this commodity requires 1500–3000 mmpa during the growing period and >1000 mmpa annually to be productive. However, total mean annual precipitation for the entire province hardly exceeds 2000 mmpa, implying inadequate rainfall for this crop. Capricorn and Waterberg barely exhibit optimal potential for litchi.

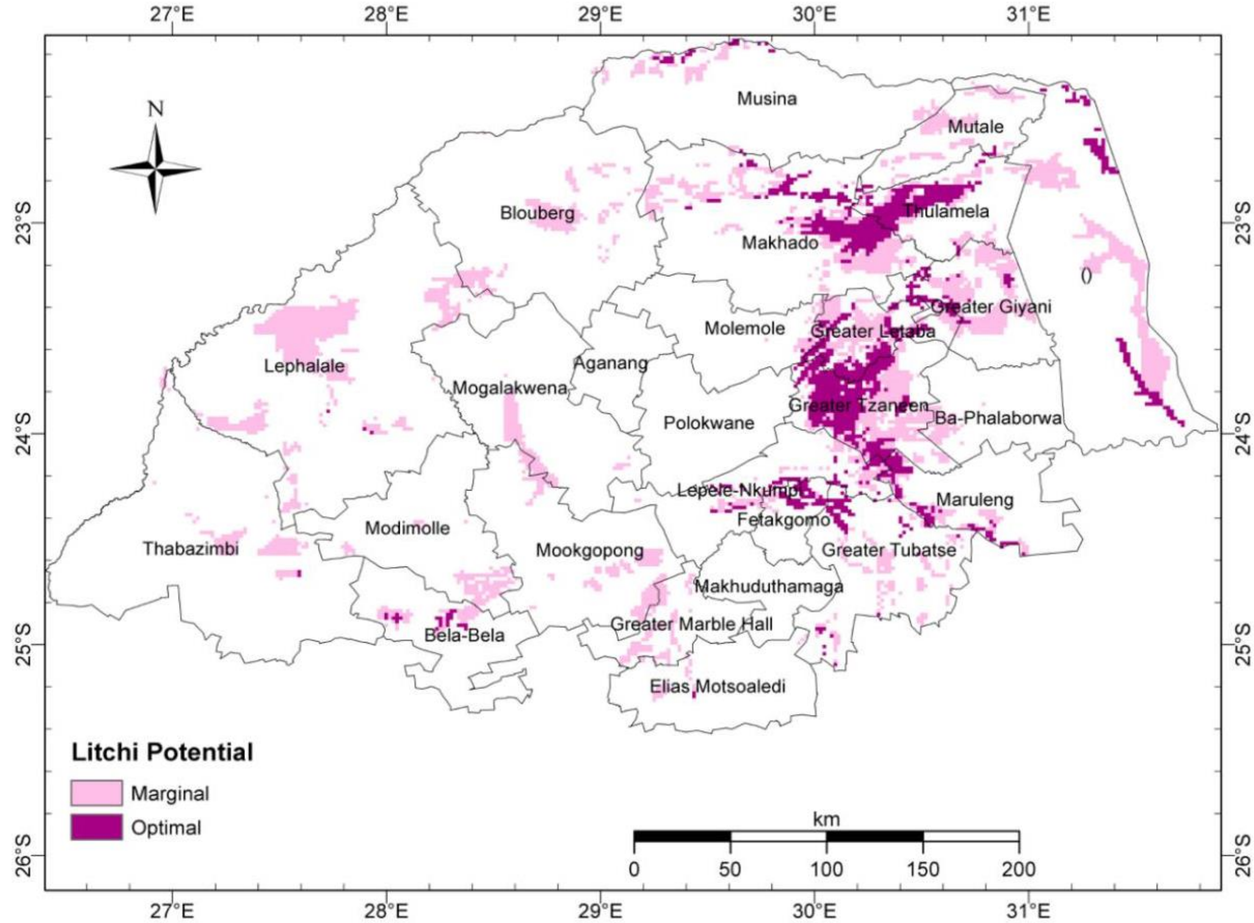

Figure-5. Spatial potential of litchi in Limpopo Province.

Thus, despite the ability of litchi to adapt to a wide array of soil types (DAIS, 2003), this implies that the vital determinant for optimal potential is water resources. This view is confirmed by the spatial correspondence between prospective areas and the mean annual rainfall map issued by ARC-ISCW (2016). On the contrary, the marginal areas for this commodity spread throughout as discontinuous patches are prominent in Capricorn (131,408 ha), Waterberg (434,440 ha), and Sekhukhune (270,156 ha; Table 2).

3.2. Groundwater-based Potential

Ndwambi et al. (2020) created a subtropical fruit (avocado, citrus, litchi, and mango) suitability model for Limpopo Province based on agro-ecological parameters and rainfed irrigation. The model established about 1 million ha of integrated (optimal and marginal suitability) prospective areas. However, such potential should not be considered as an absolute representation, because of the gradual decline in rainfall frequency and quantity (Benhin, 2006) that is the result of climate change. Nevertheless, Ndwambi et al. (2020) outlined low rainfall as the determining factor for rainfed suitability potential, despite the area conforming to subtropical regions that exhibit exceptional potential for these crops (Tshikudu, 2005).

However, Adams (2014) and Woodford and Rosewarne (2011) indicated that South Africa bears the potential for bulk groundwater potential and that there is underutilization of groundwater resources, as current abstraction rates aret about 50% of potential. Following these remarks, Ndwambi et al. (2020) asserted that crop suitability in this region should be reevaluated with the consideration of sustainable groundwater resource availability. According to Mussá, Zhou, Maskey, Masih, and Uhlenbrook (2015), groundwater is an emergency resource for countering the impact of drought. On the other hand, Sekula (2019), showed that avocado potential was significantly affected by the heatwave of 2018. However, irrigation was found to be imperative in increasing crop resilience to such a phenomenon. This instills an understanding that the mandate to incorporate groundwater resources for simulation of the suitability model not only yields to the spatial expansion of the potential but also increase crop resilience to drought.

Nevertheless, a review of crop suitability potential through integration of groundwater resources significantly improved the potential, with an additional 4.03 million ha under optimal potential and suitable potential of 8.73 million ha. Such an expansion confirms the importance of subsurface water resources in the agricultural industry (Nepal et al., 2017). Despite such a jump in potentiality, it could still be improved especially in areas not adjacent to other production activities. This is because the current model was based on 60% abstraction rates of the available resource.

3.3. Socioeconomic Benefits

South Africa is faced with crucial socioeconomic challenges ranging from unemployment to unequal distribution of resources (Alenda-Demoutiez & Mügge, 2020). These figures are likely to increase sharply due to the impacts of COVID-19. In an age of unemployment and an economy that is growing at a marginal rate (Joshua, Bekun, & Sarkodie, 2020), it is unlikely that the government will be able to tackle the issue of unemployment. However, South Africa, like any other African country, should take advantage of the globally expanding population.

It is believed that by the year 2050, global food resources are likely to increase by 38% (Mohammad & Karim, 2020) and it will then be up to this continent to cater to growing needs (Smith & Archer, 2020). The National Development Plan - Vision, 2030 (South African Government, 2012) identified agriculture as an integral sector for socioeconomic development and unemployment. The IUM approved a suitable area of 8.7 million ha. According to Phillips (2012), the ratio og labor to farm size is 1.25, which can easily be expanded with proper planning. This would imply that the sector could easily adopt at least 10.87 million employees if the government commits the necessary investment and support. These will be people that are directly employed in crop production operations. However, in reality, much work is required to prepare for agriculture that incorporates de-bushing, landscaping, fencing, irrigation canals, road networks, and energy lines. These suggest that, apart from the employees involved in farming activities, many people will be absorbed even before the commencement of operations. There are job opportunities that will arise throughout the agricultural production value chain, and many more indirect opportunities. Limpopo is recognized as the only food-secure province in South Africa; suitability models have the potential to ensure there is food security in the country.

At the dawn of the 4th Industrial Revolution, the only meaningful hope for South Africa to contribute is likely to be through agriculture. While most countries are eager to contribute significantly towards this regime, they seem to align their prospective contribution to technological advancements. While South Africa and other growing economies will be playing catch-up, they can set up agricultural hubs based on subsequent crop suitability models. The following areas were identified according to the interaction of GIS-based models as suitable to become Subtropical Hubs of Limpopo: Musina–Nwanedi corridor, Thulamela–Levubu Nandoni, Greater Tzaneen, Sekhukhune Marble Hall & Nebo, and Waterberg–Thabazimbi & Blouberg.

3.4. Tools for Planning

Delineation of the crop suitability model also serves as a fundamental spatial tool for the planning of land resources (Piikki, Winowiecki, Vågen, Parker, & Söderström, 2015). Beyond the scope of this study, the resultant crop suitability model should be used for the reservation of land for crop production; because planners appear to allocate any piece of land for settlement without prior assessment of land capability, most settlements qualify as optimal agricultural potential areas. Reservation of agricultural land will be key to ensuring that the agricultural sector can keep up with the growing food needs of the country and the planet. Crop suitability potential provides the government with an implementable tool to ensure that smallholder farmers join mainstream agricultural production. In the meantime, this model provides the government with a framework to launch subtropical fruit programs where farmers are encouraged to venture into crop production, with the government providing all necessary support to ensure the success of the program. The model also better positions the country in regard to improving earnings from foreign currency.

4. CONCLUSIONS

Groundwater is an imperative resource for sustaining the agricultural sector, particularly in semi-arid regions. The incorporation of groundwater resources as one of the predictive parameters among climatological and agro-ecological parameters that significantly expands the spatiality of optimal potential and suitable areas. The suitability model should be incorporated into the spatial decision-making process and land planning. Furthermore, the model offers greater insurance against food insecurity while also ensuring socio-economic empowerment. It also offers foundational planning towards actualization of the agro-processing and agricultural hubs.

The findings of this study suggest that crop suitability models in semi-arid regions should be established with the incorporation of the prevalent groundwater resource as a predictive parameter to optimize potential. National and provincial departments of agriculture should adopt the crop suitability model as an advisory tool for spatial planning of their spatial projects. Provincial departments of agriculture and associated district planning units should prioritize farmers in optimal potential areas for their support. Since the crop suitability model was achieved through the adoption of groundwater resources, these resources should be monitored regularly to ensure sustainability.

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Abbreviations

AHP: Analytical Hierarchy Process, ARC-ITSC: Agriculture Research Council-Institute for Tropical and Subtropical Crops, FAO: Food and Agricultural Organization, GIS: Geographical Information Systems, LDA: Limpopo Department of Agriculture, WTI: World Travel Information.

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