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Soil Temperature Characterization in Central Brazil: Exploring the Potential for Implementing Geothermal Systems

Caracterização da Temperatura do Solo no Brasil Central: Explorando o Potencial para Implementação de Sistemas Geotérmicos.

Luciane Cleonice Durante
Universidade Federal do Mato Grosso|Cuiabá|Brasil|luciane.durante@hotmail.com
Emeli Lalesca Aparecida da Guarda
Universidade Federal do Mato Grosso do Sul|Naviraí|Brasil|emeliguarda@gmail.com
Ivan Julio Apolonio Callejas
Universidade Federal do Mato Grosso|Cuiabá|Brasil|ivancallejas1973@gmail.com
Alberto Hernandez Neto
Universidade de São Paulo|São Paulo|Brasil|ahneto@usp.br
Lucas Ferrari Vera
Universidade Federal do Mato Grosso|Cuiabá|Brasil|lucas.ferrari.vera@hotmail.com

Abstract

This study investigates the potential implementation of geothermal systems in Central Brazil, focusing on historical and future soil temperature conditions. The soil's distinct thermophysical properties result in a slower response to climatic variations, creating a temperature gradient known as soil thermal inertia. The research analyzes soil temperature correlations with altitude and climate change in selected Mato Grosso municipalities for historical, 2050, and 2080 periods. The findings reveal a robust correlation between altitude and historical soil temperature, indicating varied geothermal potential. However, 2050 and 2080 projections show significant potential reduction due to climate change impacts, especially in lower-altitude regions. The positive correlation between soil and air temperatures highlights their close relationship, crucial for assessing geothermal potential under climate change. The results emphasize the importance of considering climate projections in geothermal planning and suggest geothermal energy as a sustainable cooling solution for Mato Grosso's agricultural buildings, adapting to evolving thermal conditions.

Keywords: Geothermal Energy. Climate Change. Soil Temperature. Sustainable Implementation. Agricultural Cooling.

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Resumo

Este estudo investiga o potencial de implementação de sistemas geotérmicos no Centro-Oeste do Brasil, com foco nas condições climáticas históricas e futuras da temperatura do solo. As propriedades termofísicas distintas do solo em relação ao ar resultam em uma resposta mais lenta às variações climáticas, criando um gradiente de temperatura conhecido como inércia térmica do solo. A pesquisa analisa as correlações entre a temperatura do solo, altitude e mudanças climáticas em municípios selecionados do Mato Grosso para os períodos histórico, 2050 e 2080. Os resultados revelam uma correlação robusta entre altitude e temperatura histórica do solo, indicando potenciais geotérmicos variados. No entanto, as projeções para 2050 e 2080 mostram uma redução significativa no potencial devido aos impactos das mudanças climáticas, especialmente em regiões de baixa altitude. A correlação positiva entre as temperaturas do solo e do ar destaca sua estreita relação, crucial para a avaliação do potencial geotérmico no contexto das mudanças climáticas. Os resultados enfatizam a importância de considerar as projeções climáticas no planejamento geotérmico e sugerem a energia geotérmica como uma solução de resfriamento sustentável para as edificações agrícolas do Mato Grosso, adaptando-se às condições térmicas em evolução.

Resumo: Energia Geotérmica. Mudanças Climáticas. Temperatura do Solo. Implementação Sustentável. Refrigeração Agrícola.

INTRODUCTION

The soil represents a natural source of heat and cold due to its thermophysical properties, which differ from those of the air. This distinction results in a slower response of the soil to heat transfer mechanisms caused by daily and annual variations in surface climatic conditions [1]. The disparity in properties between the soil and the ambient air establishes a temperature gradient known as soil thermal inertia. This thermal behavior varies depending on climatic conditions, soil type, and local factors such as ground cover, moisture content, and thermal anomalies.

In this context, soil temperature is determined by the interaction of absorbed radiation (heating), reflected long-wave radiation, convective exchange between the soil and ambient air, and heat transfer between the surface and deeper layers of the soil [2]. Thus, the soil temperature distribution profile can be divided into three zones: the shallow zone (0-1m depth), the intermediate zone (1-10m depth), and the deep zone (+10m depth). The shallow zone is strongly influenced by daily temperature fluctuations and is affected by atmospheric conditions. The intermediate zone depends mainly on the seasonal cycle, representing a more stable layer similar to air temperature. On the other hand, the deep zone exhibits almost constant variations and depends exclusively on the geothermal gradient [3]. As a result, the intermediate zone shows a slow response to temperature variations, appearing cooler in summer and warmer in winter [2]. Therefore, this characteristic of the layer can be considered a bioclimatic strategy to improve building thermal performance.

In recent years, the direct use of geothermal energy has increased its installed capacity on a global scale [3]. The main application of ground energy is in building conditioning, fueling interest and the need to develop or improve predictive models capable of estimating soil temperature variations at shallower depths. Thus, the aim of this research is to investigate the potential implementation of geothermal systems in

Central Brazil based on the analysis of historical and future climatic conditions of soil temperature.

METHODOLOGY

DEVELOPMENT OF FUTURE CLIMATIC SCENARIOS

The Morphing method has been employed to mathematically transform current climates into future climates, considering scenarios of climate change [6]. The Future Weather Generator tool utilizes the Morphing methodology to make climate projections, illustrating monthly changes in climatic variables. This tool is based on the GCM model EC-Earth3, which is part of the CMIP6 project and serves as the foundation for the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) [7].

The tool utilizes a base climatic period for the projections from 1985 to 2014 and generates future climatic files for 2050 (period 2036-2065) and 2080 (period 2066-2095) for emission scenarios SSP2-4.5, SSP3-7.0, and SSP5-8.5. It presents the results as future climatic files in the EPW format, widely used in thermal and energy performance simulations of buildings and cities.

Additionally, the tool was developed in the Java programming language, and its source code is freely available under the Creative Commons Attribution 4.0 Share-Alike license [8]. To make its use more accessible for simulators and designers, the authors created a graphical interface that allows the insertion of historical climatic files and, consequently, the generation of future climatic scenarios.

In this research, the SSP5-8.5 scenario, labeled as "pessimistic" by the AR6 [7], was chosen for the projections of 2050 and 2080. The base climatic files for the cities consist of the Solar and Wind Energy Resource Assessment (SWERA) due to its better alignment with the historical period used as the basis for the projections, as indicated in the tool's documentation.

CHARACTERIZATION OF STUDY REGIONS

For the characterization of the region, 141 municipalities located in the state of Mato Grosso, in the Central-West region of Brazil, were selected. The majority of the state is represented by the Aw climatic type (tropical with summer rains), covering approximately 90% of its territory, while approximately 10% is classified as the Am climatic type (tropical with monsoon climate). This climatic classification is commonly found in various regions worldwide, located between the Tropics of Cancer and Capricorn, and is the second most prevalent climate type, covering about 11.5% of the Earth's land area [5]. Additionally, the representative biomes of the state are the Amazon Rainforest, the Cerrado, and the Pantanal.

The characterization was carried out by filtering municipalities that have climatic data obtained from meteorological stations recording information on soil temperature. These stations are part of the National Institute of Meteorology (INMET) network and measure soil temperature at depths of 0.50 cm, 2.0 m, and 4.0 m. After this filtering process, it was found that only 34 municipalities have soil temperature data.

Table 1: Description of the study regions

City	Long.	Lat.	Alt.	Biome
Água Boa	14°1.0'	52°13.0'	434m	CE
Alta Floresta	17°49.0'	53°16.9'	289m	AM
Alto Taquari	9°51.9'	56°6.3'	877m	CE
Apiacas	9°34.0'	57°24.0'	222m	AM
Barra do Garças	15°51.6'	52°23.3'	350m	CE
Caceres	16°3.0'	57°40.9'	118m	PA e CE
Campo Novo dos Parecis	13°46.9'	57°49.9'	572m	CE
Campo Verde	15°31.9'	55°7.9'	751m	CE
Canarana	13°30.0'	52°30.0'	430m	CE
Carlinda	9°58.0'	55°49.9'	302m	AM
Comodoro	13°43.0'	59°46.0'	593m	CE
Cotriguaçu	9°54.3'	58°34.3'	263m	AM
Cuiabá	15°39.1'	56°7.0'	188m	CE e PA
Diamatino	14°24.0'	56°27.0'	286m	CE
Gaúcha do Norte	13°10.9'	53°15.0'	381m	CE
Gleba Celeste (Vera)	12°12.0'	56°30.0'	415m	CE
Guiratinga	16°21.0'	53°46.0'	528m	CE
Juara	11°16.9'	57°31.9'	262m	CE
Juina	11°22.9'	58°46.9'	376m	AM
Matupa	10°15.0'	54°55.0'	285m	AM
Nova Maringá	13°1.9'	57°6.0'	355m	CE
Nova Xavantina	14°42.0'	52°21.0'	315m	CE
Novo Mundo	12°31.0'	58°13.9'	433m	CE
Paranatinga	14°25.0'	54°1.9'	476m	CE
Porto Estrela	15°19.5'	57°13.5'	147m	CE
Poxoreo	15°49.9'	54°22.9'	450m	CE
Querência	12°37.9'	52°13.0'	384m	CE
Rondonópolis	16°27.0'	54°34.0'	286m	CE
Salto do céu	15°7.5'	58°7.6'	305m	AM
São Felix do Araguaia	11°37.0'	50°43.9'	220m	CE
São José do Rio Claro	13°27.0'	56°40.0'	352m	CE
Sinop	11°58.9'	55°34.0'	373m	CE
Sorisso	12°33.0'	55°43.0'	382m	CE
Tangará da Serra	14°39.0'	57°25.9'	323m	CE

*Legend: Amazon Rainforest (AM), Cerrado (CE), and Pantanal (PA) Biomes

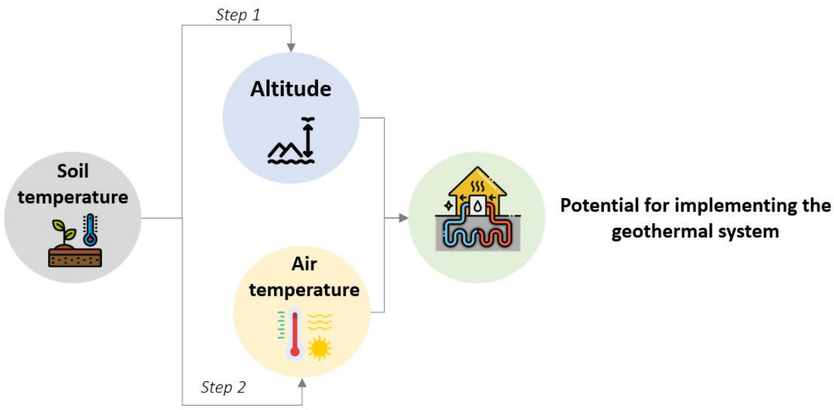
Source: Author.

CHARACTERIZATION OF SOIL TEMPERATURES: THE GEOTHERMAL SYSTEM POTENTIAL FOR THE STATE OF MATO GROSSO

To analyze the potential implementation of geothermal systems in the state of Mato Grosso, three stages were conducted to characterize soil temperatures. The first phase involved analyzing the correlation between soil temperature (°C) in historical and future periods (2050 and 2080) and the altitude (m) of each city. For this purpose, the annual average soil temperature at a depth of 2 meters was used, extracted from the climatic files of each analyzed city. The aim was to examine the relationship between soil temperature and altitude, thereby identifying municipalities with potential for the implementation of geothermal systems.

Subsequently, an investigation into the soil temperature profile at a depth of 2 meters in relation to air temperature was carried out in the historical period and in the SSP5-8.5 scenario for the years 2050 and 2080. This analysis aimed to assess the impact of climate change on these variables. For these characterizations, meteorological stations in Cuiabá, São Félix do Araguaia, and Matupá were excluded due to a lack of climatic data. Figure 1 presents the flowchart of the methodological process.

Figure 1: Flowchart of the methodological process for characterizing the implementation potential of the geothermal system



Source: Author.

To determine the potential for the implementation of geothermal systems, temperature limits for the soil were established. These limits were defined as presented in Table 2.

Table 2: Ranges of implementation potential for the geothermal system in the state of Mato Grosso

Ranges	Geothermal System Implementation Potential for the Savannah Region
≤24.0°C	Very High Potential – Cold soil temperatures
>24.0 and ≤26.0°C	High Potential – Moderate soil temperatures
>26.0 and ≤28.0°C	Medium Potential – Slightly warm soil temperatures
>28.0 and ≤30.0°C	Low Potential – Hot soil temperatures
>30.0°C	Very Low Potential – Very hot soil temperatures

Source: Author.

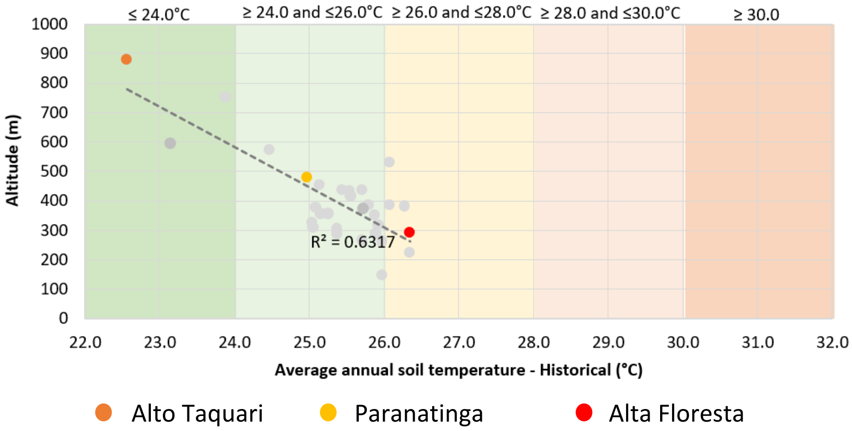
RESULTS AND DISCUSSIONS

RELATIONSHIP BETWEEN ALTITUDE AND SOIL TEMPERATURE: A TEMPORAL ANALYSIS OF THE PAST AND FUTURE PERSPECTIVES

In the initial phase of this study, a correlation was established between the annual average soil temperature at a depth of 2.0 meters and the altitude of the investigated locations, covering both the historical period and future scenarios (2050 and 2080).

During the historical period, a robust positive linear correlation between these variables was observed, as evidenced by the correlation coefficient of 0.6317 (Figure 2). Notably, cities with distinct altitudes—Alto Taquari (higher altitude), Paranatinga (medium altitude), and Alta Floresta (lower altitude)—demonstrated different potentials for the implementation of geothermal systems. In Alto Taquari, the soil temperature remains within the range of <24.0°C, indicating a high potential for the implementation of geothermal systems. However, as altitude decreases, both the soil temperature and the potential for system implementation decrease, as evidenced in Alta Floresta, where the soil temperature varies from >26.0°C to ≤28.0°C (Figure 2). During this period, only two cities recorded soil temperatures below 24.0°C, while the majority fell within the range of >24.0°C to ≤26.0°C. Five cities exhibited elevated soil temperatures, namely Guiratinga, Sorriso, Gaúcha do Norte, Apiacás, and Alta Floresta (Table 3).

Figure 2: Correlation between the soil temperature at 2.0 meters and the altitude of locations in the historical period



Source: Author.

Table 3: Cities and their respective ranges of geothermal system implementation in the historical period

Ranges	Cities
≤24.0°C	**Alto Taquari**; Comodoro
>24.0 and ≤26.0°C	Campo Verde; Campo Novo dos Parecis; **Paranatinga**; Tangará da Serra; Salto do céu; Juína; Poxoréo; São José do Rio Claro; Nova Maringá; Diamantino; Carlinda; Novo Mundo; Canarana; Gleba Celeste (Vera); Água Boa; Cotriguaçu; Sinop; Querência; Barra dos Garças; Rondonópolis; Nova Xavantina; Porto Estrela; Juara
>26.0 and ≤28.0°C	Guiratinga; Sorriso; Gaúcha do Norte; Apiacás; **Alta Floresta**
>28.0 and ≤30.0°C	-
>30.0°C	-

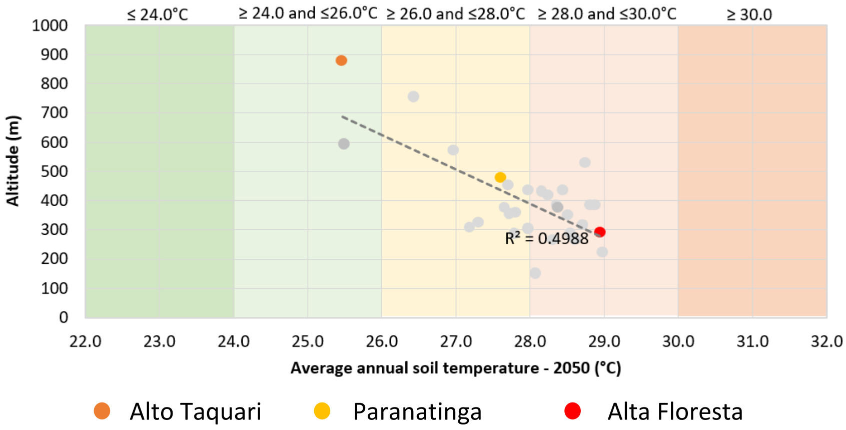
Source: Author.

In the year 2050, there is a notable low positive linear correlation between the analyzed variables, as evidenced by the correlation coefficient of 0.4988 (Figure 3). In this context, it becomes apparent that, due to the impacts of climate change, there is a reduction in the potential for implementing geothermal systems, characterized by an increase in soil temperatures.

Soil temperatures in Alto Taquari experience an increase, ranging from >24.0°C to ≤26.0°C. This trend is similarly observed in the cities of Paranatinga and Alta Floresta, transitioning to ranges of >26.0°C to ≤28.0°C and >28.0°C to ≤30.0°C, respectively (Figure 3). This thermal behavior demonstrates the direct influence of climate change, indicating a future scenario of warming soil temperatures in these locations. In 2050, due to the impacts of climate change, no cities recorded soil temperatures below

24.0°C. Predominantly, temperatures were in the range of >26.0°C to ≤30.0°C (Table 4).

Figure 3: Correlation between the soil temperature at 2.0 meters and the altitude of locations in the year 2050



Source: Author.

Table 4: Cities and their respective ranges of geothermal system implementation in the year 2050

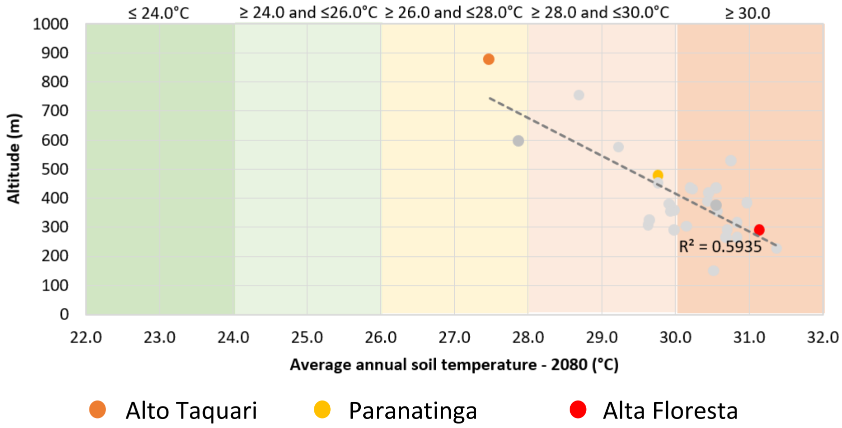
Ranges	Cities
<24.0°C	-
>24.0 and ≤26.0°C	**Alto Taquari**; Comodoro; Campo Verde
>26.0 and ≤28.0°C	Campo Verde; Campo Novo dos Parecis; Salto do céu; Tangará da Serra; **Paranatinga**; Juína; Poxoréo; São José do Rio Claro; Diamantino; Nova Maringá; Novo Mundo; Carlinda
>28.0 and ≤30.0°C	Porto Estrela; Canarana; Gleba Celeste (Vera); Cotriguaçu Querência; Sinop; Água Boa; Barra dos Garças; Rondonópolis; Juara; Nova Xavantina; Guiratinga; Sorriso Gaúcha do Norte; **Alta Floresta**; Apiacás
>30.0°C	-

Source: Author.

In the year 2080, a positive linear correlation is noteworthy between the analyzed variables, as evidenced by the correlation coefficient of 0.5933 (Figure 4). In this scenario, it is observed that, due to the impacts of climate change, there is a significant reduction in the potential for implementing geothermal systems, characterized by the increase in air temperatures and, consequently, soil temperatures.

Soil temperatures exceed 26.0°C in Alto Taquari, while in Alta Floresta, soil temperatures surpass 30.0°C. This indicates that the potential for implementing geothermal systems becomes low in regions with lower altitudes, as the soil is warmer. In contrast, in regions with higher altitudes, such as Alto Taquari, the implementation of the system still appears viable, even with temperatures exceeding 26.0°C. In 2080, no cities recorded soil temperatures below 26.0°C, and higher soil temperatures above 30.0°C were more predominant (Table 5).

Figure 4: Correlation between the soil temperature at 2.0 meters and the altitude of locations in the year 2080



Source: Author.

Table 5: Cities and their respective ranges of geothermal system implementation in the year 2080

Ranges	Cities
<24.0°C	-
>24.0 and ≤26.0°C	-
>26.0 and ≤28.0°C	**Alto Taquari**; Comodoro
>28.0 and ≤30.0°C	Campo Verde; Campo Novo dos Parecis; Salto do céu; Tangará da Serra; **Paranatinga**; Poxoréo; Juína; São José do Rio Claro; Nova Maringá
>30.0°C	Diamantino; Carlinda; Novo Mundo; Canarana; Querência; Gleba Celeste (Vera); Porto Estrela; Sinop; Água Boa; Barra dos Garças; Cotriguaçu; Rondonópolis; Guiratinga; Nova Xavantina; Juara; Gaúcha do Norte; Sorriso; **Alta Floresta**; Apiacás

Source: Author.

Thus, a positive correlation is observed in the historical period, indicating varied potentials for the implementation of geothermal systems at different altitudes. However, projections for 2050 suggest a reduction in this potential due to the impacts of climate change, as evidenced by the increase in soil temperatures. In the 2080 scenario, the correlation persists, highlighting a significant decrease in the potential for implementing geothermal systems, especially in regions of lower altitude.

CONCLUSIONS

This research provided a comprehensive analysis of the correlation between soil temperature, altitude, and climate change, considering historical, 2050, and 2080 periods. In the historical period, a robust correlation between altitude and soil temperature was observed, indicating varied potentials for the implementation of geothermal systems at different altitudes. The cities of Alto Taquari, Paranatinga, and Alta Floresta manifested distinct potentials, influenced by altitude and climatic conditions.

However, projections for 2050 and 2080 reveal a significant reduction in the potential for implementing geothermal systems. The increase in soil temperatures due to the impacts of climate change emerged as a limiting factor, especially in regions of lower altitude. In 2050, a considerable increase in soil temperatures was already observed, indicating a decrease in the potential for geothermal system implementation. This scenario intensified in 2080, with soil temperatures surpassing acceptable limits for the effectiveness of these systems in various locations.

The positive correlation between soil temperature at a depth of 2 meters and air temperature, evident in all analyzed periods, suggests a close relationship between these climatic parameters. This understanding is crucial for assessing the potential of geothermal systems in the face of climate change.

In summary, the results highlight the need to consider climate projections when planning the implementation of geothermal systems, adjusting strategies as thermal conditions evolve over time. Furthermore, these initial findings suggest that geothermal energy may offer a viable and sustainable cooling solution for agricultural buildings in Mato Grosso, considering the specific soil temperature ranges and geographical characteristics of the selected regions.

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