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Graph Coloring on the Primary Dryland Forest Cover Map of Kalimantan Using the Greedy Algorithm

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ABSTRACT

Dalam teori graf, teknik pewarnaan graf menjadi salah satu pendekatan populer, termasuk dalam pembuatan peta, dan penelitian ini bertujuan menerapkan algoritma Greedy untuk mewarnai peta penutupan lahan hutan dengan memastikan wilayah yang bersebelahan tidak memiliki warna yang sama. Data yang digunakan berupa peta klasifikasi penutupan lahan dan hubungan antar wilayah yang direpresentasikan sebagai graf planar. Algoritma Greedy dijalankan dengan menyusun simpul berdasarkan derajat tertinggi, kemudian mewarnai simpul secara berurutan. Hasil pewarnaan menunjukkan bahwa algoritma ini mampu memberikan solusi efisien dengan jumlah warna minimum sesuai batas atas pewarnaan graf, khususnya pada peta penutupan lahan hutan kering primer di Provinsi Kalimantan, yang berhasil dicapai dengan bilangan kromatik $\chi(G) = 4$, sehingga menjamin tidak ada wilayah bertetangga yang memiliki warna sama. Meskipun tidak selalu menghasilkan solusi optimal, algoritma ini terbukti efektif, sederhana, dan dapat diterapkan untuk berbagai aplikasi lain seperti analisis spasial, pengelompokan wilayah, atau sistem informasi geografis. Kebaruan penelitian terletak pada penerapan pada hutan kering primer di Kalimantan, yang sebelumnya jarang dikaji, serta kontribusinya pada analisis spasial dan konservasi wilayah.

In graph theory, graph coloring is a popular approach, including in map creation, and this study aims to apply the Greedy algorithm to color forest land-cover maps while ensuring that adjacent areas do not share the same color. The data used consist of land-cover classification maps and the relationships between regions represented as planar graphs. The Greedy algorithm is implemented by arranging nodes based on their highest degrees and then coloring them sequentially. The coloring results show that the algorithm can provide an efficient solution with a minimum number of colors according to the upper bound of graph coloring, particularly for primary dry forest land-cover maps in East Kalimantan Province, achieving a chromatic number $\chi(G) = 4$, ensuring no neighboring areas share the same color. Although it does not always yield an optimal solution, the algorithm proves effective, simple, and applicable to various other uses such as spatial analysis, regional clustering, or geographic information systems. The novelty of this study lies in its application to primary dry forests in Kalimantan, which have been rarely explored, and its contribution to spatial analysis and conservation efforts.

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INTRODUCTION

Graph theory is a branch of mathematics that studies the relationships among elements in a non-empty set consisting of vertices (points) and edges (pairs of vertices) (Mamathi et al., 2020). Leonhard Euler first introduced graph theory in 1736 through the Königsberg Bridge problem, and it has since rapidly developed in various fields, particularly mathematics and computer science. Formally, a graph is defined as an ordered pair of sets $G = (V, E)$ where V is a non-empty set of vertices and E is a set of edges. A graph may have no edges but must contain at least one vertex (Munir, 2016). One of the key concepts in graph theory is graph coloring, which refers to the assignment of colors to graph elements such as vertices, edges, or regions, with the rule that two adjacent vertices must not share the same color. This concept is widely applied, including in map coloring to facilitate the visualization of relationships between regions (Pamungkas et al., 2018).

In graph theory, the graph coloring method is one approach used to assign colors to each vertex, with the rule that no two adjacent vertices share the same color. Typically, this is done by assigning different colors to each vertex to avoid color conflicts. An important application of this concept is map coloring, where graph theory helps visualize interregional relationships for easier understanding (Qomaruddin et al., 2022). Region coloring was one of the earliest problems in graph coloring theory, which requires that every adjacent area be assigned a different color to facilitate identification (Himayati et al., 2023).

Land cover describes the physical condition of the Earth's surface materials as well as the interaction between natural and social processes. Cumulative forest degradation can trigger climate change. Increasing use of natural resources shows that the main factor driving exploitation is the economic needs of local communities. Adhimatta et al. (2020) stated that regional economic growth can indeed directly improve welfare but, on the other hand, also drives higher land demand. Land-use change is influenced by urban expansion, infrastructure development, and shifts in the concentration of certain activities (Sabar et al., 2024). In addition, population growth in various regions contributes to increased land use and land conversion. Land use generally refers to human intervention in land, either permanently or cyclically. Overall, changes in land utilization and use are part of both natural dynamics and human life, but they also have the potential to create ecosystem imbalances (Sabar et al., 2024).

Primary dry forest is a type of forest that has not experienced significant disturbance or alteration due to human activities, thus maintaining its natural and intact ecosystem. Primary dry forest cover refers to the extent of forest area still covered by natural vegetation. However, the extent of primary dry forest cover has beencontinuously declining due to deforestation, land conversion for agriculture, infrastructure development, and various other human activities. This decline negatively affects biodiversity, the ecological functions of forests, as well as their role in carbon sequestration and climate regulation. Therefore, more intensive conservation efforts are required, such as reforestation, sustainable forest management, and law enforcement against illegal activities that could damage forest ecosystems (Harianto et al., 2022).

The Greedy Method is a fairly efficient approach in solving graph coloring problems, particularly in map coloring. This algorithm is often used in optimization, both for maximization and minimization, through a step-by-step approach that always selects the locally optimal choice in order to reach an overall optimal solution (Himayati et al., 2023). In its application, the Greedy Algorithm searches for a solution set from a given set that must satisfy the conditions of being an optimal solution based on an objective function. In graph coloring, this algorithm determines the order of vertices and assigns each vertex the first available color, ensuring that no two adjacent vertices share the same color (Putra et al., 2024).

Several previous studies are aligned with this research. A study by Umi Maftukhah et al. (2020) applied the Greedy Algorithm to efficiently solve the problem of administrative region coloring. Furthermore, research conducted by Ade Novia Rahma et al. (2021) discussed the application of the Greedy Algorithm in map coloring to ensure that adjacent regions had different colors with the minimum number of colors possible. Then, research by Khuzamiah and Riza (2023) highlighted how this algorithm could be used to optimize map coloring on a smaller scale. More recently, a study by Angginy Akhirunnisa et al. (2023) implemented the Greedy Algorithm in graph coloring for the Medan City area, aiming to find the minimum number of colors in the graph representation of a region, as well as to support land-use planning, resource distribution, and scheduling of activities across adjacent areas.

This study aims to apply the Greedy Algorithm in the process of graph coloring representing the land cover map of primary dry forests in Kalimantan, with a focus on determining the minimum number of colors so that adjacent areas have different colors. The novelty of this research lies in its application to the scale of primary dry forest areas in Kalimantan, which present different topological complexities and data limitations compared to previous urban based studies. In addition, the specific contribution of this study is to produce a color mapping that facilitates more effective analysis of land use and land cover, while also supporting conservation efforts through sustainable land-use planning. This research is expected to provide a significant contribution to forest management in Kalimantan and enrich the study of graph theory and its applications in ecological contexts.

METHOD

This research employs a literature study by reviewing sources such as books and journals related to graph coloring theory and the Greedy Algorithm. The data used consist of the primary dry forest land cover map in Kalimantan, obtained from the Interactive Map of SIGAP KLHK. The map is modeled as a graph, with each region represented as a vertex and the boundaries between regions represented as edges in the graph. The Greedy Algorithm is applied to color the graph with the objective of minimizing the number of colors required. The final stage of the research involves analyzing the coloring results to support more effective forest area mapping and management.

According to Jofie et al. (2020), the Greedy Algorithm is a step-by-step problem-solving method used in optimization, based on the principle of choosing the best option at each stage to achieve an overall optimal solution. In the context of graph coloring, the steps of the algorithm include:

1. Preparing a candidate set (C) consisting of the elements that make up the solution.
2. Initializing the solution set (S) as an empty set with no elements.
3. Selecting a vertex to be colored based on the highest degree using the color selection function.
4. Choosing a candidate color through the color selection function.
5. Checking the feasibility of the selected color for the chosen vertex in two stages:
   - If the color from the solution set S is feasible (no conflict with adjacent vertices), it is chosen for coloring.
   - If no feasible color exists, a new color from the candidate set C is selected.
6. Adding the chosen color into the solution set S if considered feasible.
7. Evaluating the coloring using the objective function. If all vertices are colored, the process is complete; otherwise, repeat the vertex selection step.

Figure 1 presents the flowchart of the graph coloring algorithm using the Greedy Algorithm. This diagram illustrates the systematic steps adapted from Mussafi (2015), who applied the algorithm to the regional map of Yogyakarta Municipality.

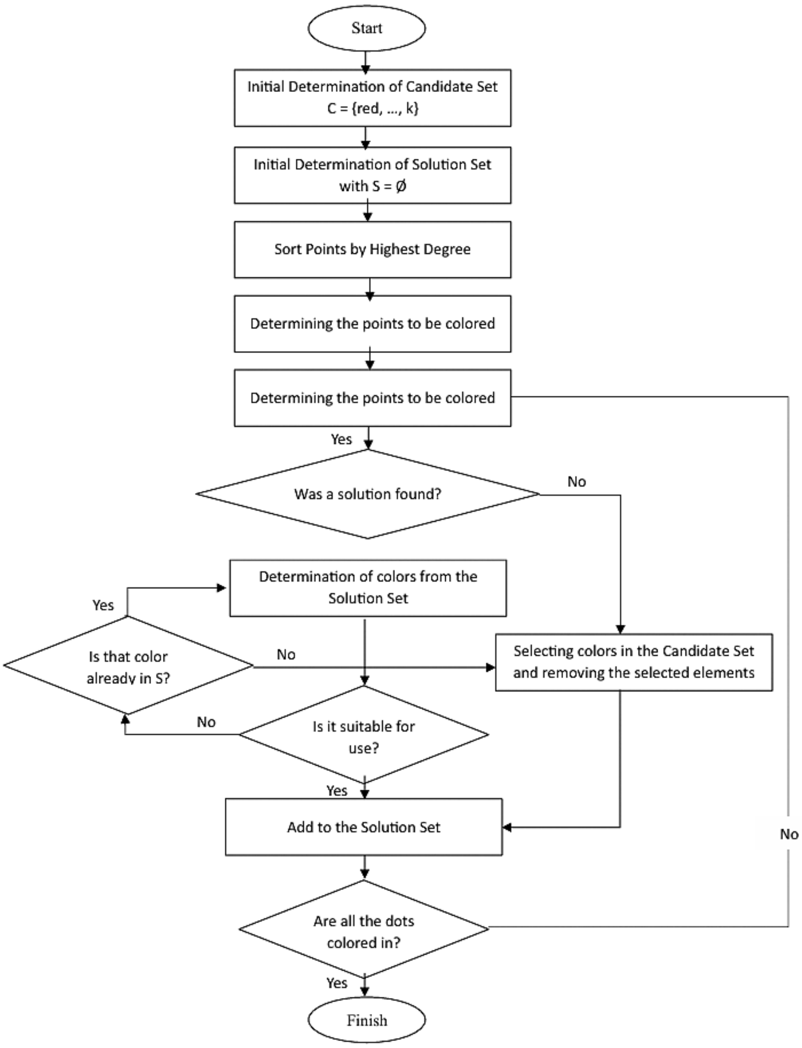

Figure 1. Flowchart Of Graph Coloring Using The Greedy Algorithm

RESULTS

The graph representation of the Kalimantan regional map can be illustrated through the visualization of interconnections among its administrative areas. Figure 2 depicts the map of Kalimantan, consisting of 56 regencies/municipalities, each sharing common boundaries with adjacent regions. This map can be represented in the form of a graph, in which the boundaries between regencies/municipalities are modeled as edges, while the points of intersection or adjacency between regions are represented as vertices.

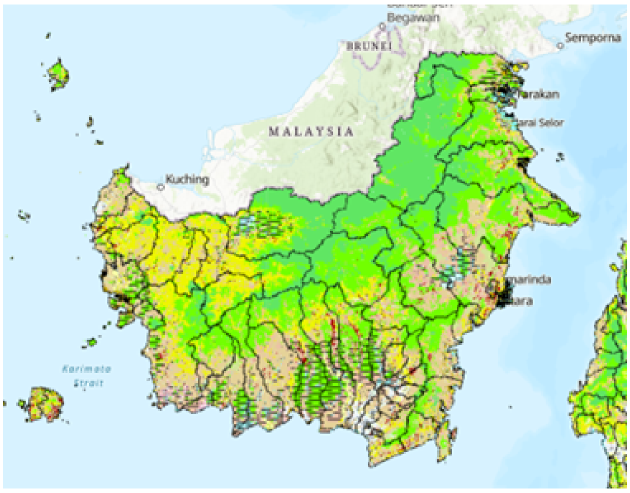

Figure 2. The Kalimantan Regional Map
(Source: Peta Interaktif SIGAP Kementerian LHK)

The map of primary dryland forests in the Kalimantan region can be represented in the form of a graph, in which the boundaries between regions are modeled as edges and the intersections between regions as vertices. This representation provides a mathematical illustration of the interconnectivity among regions. The present study focuses on the Kalimantan region, in which, out of a total of 56 regencies/municipalities, 34 are recorded as containing primary dryland forests, as shown in Figure 3.

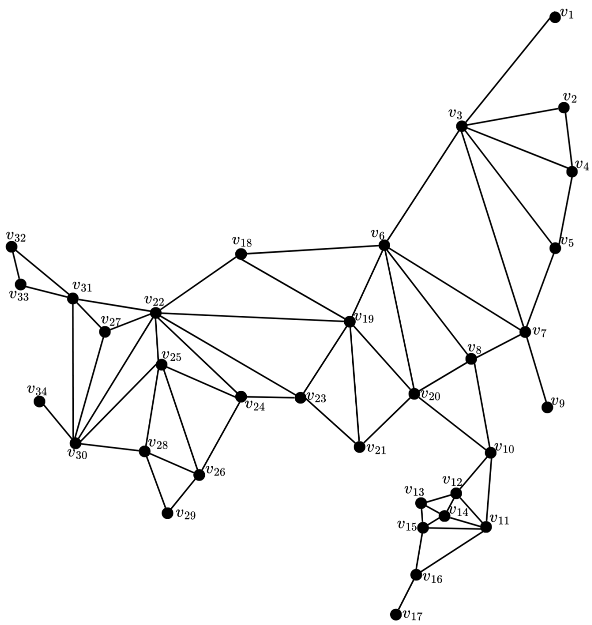

Figure 3. Graph-Based Representation Of Primary Dryland Forests in Kalimantan.

In Figure 3, each vertex represents a regency/municipality located in the Kalimantan regional. The interrelations among these vertices in the graph are further detailed in Table 1.

Table 1. Representation of Vertices in the Primary Dryland Forests of Kalimantan Regional

No.	Vertices	Regency/Municipalit	No.	Vertices	Regency/Municipality
1.	v_1	Nunukan	18.	v_{18}	Kapuas Hulu
2.	v_2	Bulungan	19.	v_{19}	Murung Raya
3.	v_3	Malinau	20.	v_{20}	Barito Utara
4.	v_4	Berau	21.	v_{21}	Kapuas
5.	v_5	Kutai Timur	22.	v_{22}	Sintang
6.	v_6	Mahakam Ulu	23.	v_{23}	Gunung Mas
7.	v_7	Kutai Kartanegara	24.	v_{24}	Katingan
8.	v_8	Kutai Barat	25.	v_{25}	Melawi
9.	v_9	Balikpapan	26.	v_{26}	Seruyan
10.	v_{10}	Paser	27.	v_{27}	Sekadau
11.	v_{11}	Kota Baru	28.	v_{28}	Lamandau
12.	v_{12}	Balangan	29.	v_{29}	Kota Waringin Barat
13.	v_{13}	Hulu Sungai Utara	30.	v_{30}	Ketapang
14.	v_{14}	Hulu Sungai Tengah	31.	v_{31}	Sanggau
15.	v_{15}	Hulu Sungai Selatan	32.	v_{32}	Bengkayang
16.	v_{16}	Banjar	33.	v_{33}	Landak
17.	v_{17}	Tanah Laut	34.	v_{34}	Kayong Utara

Subsequently, the degree of each vertex corresponding to the regencies/municipalities is determined based on Figure 3. Table 2 is constructed with reference to that figure, providing a detailed representation of the number of connections associated with each vertex in the graph, thereby offering clearer information on the degree or level of connectivity of each vertex.

Table 2. Degree of Vertices In Graph of Primary Dryland Forests in Kalimantan Regional

Vertices	Regency/Munici	Vertices	Regency/Municipality
v_1	1	v_{18}	3
v_2	2	v_{19}	6
v_3	6	v_{20}	5
v_4	3	v_{21}	3
v_5	3	v_{22}	8
v_6	6	v_{23}	4
v_7	5	v_{24}	4
v_8	4	v_{25}	5
v_9	1	v_{26}	4
v_{10}	4	v_{27}	3
v_{11}	5	v_{28}	4
v_{12}	4	v_{29}	2
v_{13}	3	v_{30}	6
v_{14}	4	v_{31}	5
v_{15}	4	v_{32}	2
v_{16}	3	v_{33}	2
v_{17}	1	v_{34}	1

The Greedy Algorithm is applied in the process of coloring the map of the Kalimantan Region through the following steps:

1. Constructing the Candidate Color Set C
   The candidate set C consists of colors to be used in the map-coloring process of the Kalimantan Region. Six colors are used, namely $C = \{$Red, Yellow, Green, Blue, Purple, Pink$\}$.
2. Preparing the Initial Solution Set S
   This step begins with defining the solution set as an empty set. The solution set will eventually contain the colors assigned to the vertices of the map. The initial solution set is denoted as $S = \{\}$.
3. Ordering Vertices by Highest Degree
   Based on the data in Table 2, Table 3 is constructed to arrange the vertices from the highest to the lowest degree.

Table 3. Degree of Vertice in Graph Of Map The Kalimantan Region

Vertices	Regency/Munici	Vertices	Regency/Municipality
v_{22}	8	v_{26}	4
v_{3}	6	v_{28}	4
v_{6}	6	v_{4}	3
v_{19}	6	v_{5}	3
v_{30}	6	v_{13}	3
v_{7}	5	v_{16}	3
v_{11}	5	v_{18}	3
v_{20}	5	v_{21}	3
v_{25}	5	v_{27}	3
v_{31}	5	v_{2}	2
v_{8}	4	v_{29}	2
v_{10}	4	v_{32}	2
v_{12}	4	v_{33}	2
v_{14}	4	v_{1}	1
v_{15}	4	v_{9}	1
v_{23}	4	v_{17}	1
v_{24}	4	v_{34}	1

4. Selection Function
   Before the graph coloring process is carried out, it is necessary to establish an efficient strategy for selecting vertices and colors to ensure that the coloring satisfies the required conditions. Therefore, this stage begins with a selection function consisting of two parts: vertex selection and color selection.

   a. Vertex Selection Function
      In the initial stage of vertex selection, the starting vertex to be colored is determined. The vertex with the highest degree is prioritized in the coloring process. As shown in Table 2, the vertex with the highest degree is v_{22}, therefore vertex v_{22} is chosen as the initial step.

   b. Color Selection Function
      The next step is to select the color to be used to vertex v_{22}. This color selection process consists of two steps. The first step is to select a color from the existing solution set and test its feasibility to ensure it can be reused without causing conflicts with adjacent vertices. If no color in the solution set satisfies the condition, or if no color has yet been used in the solution set, then a new color is chosen from the candidate set C that has not been previously used.
      In the case of select the color to vertex v_{22}, the selection begins by taking a color from the candidate set. The first choice is choose the red color from the candidate set C. Once the red color is used, the candidate set is reduced by one element, leaving five colors: $C = \{$Yellow, Green, Blue, Purple, Pink$\}$. The graph coloring process can be seen in Figure 4.

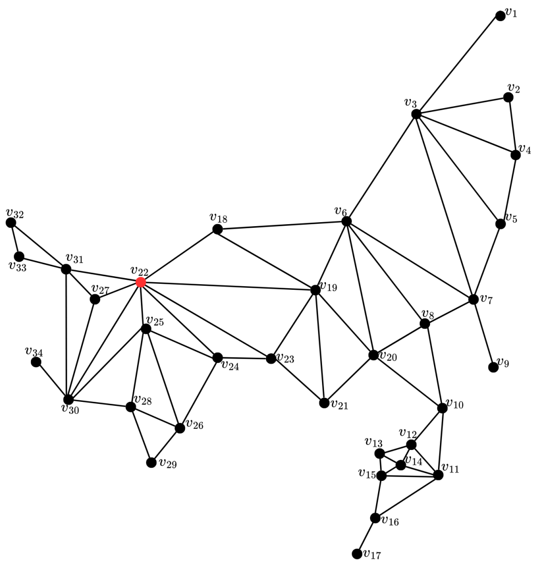

Figure 4. Coloring in Vertex v_{22}

5. Feasibility Function
   The suitability of using the red color for vertex v_{22} is examined based on its adjacency matrix. Since vertex v_{22} is adjacent to eight vertices that have not yet been assigned a color, the red color can be applied to vertex v_{22}.
6. Solution Set
   After assigning the red color to vertex v_{22}, this color is automatically included in the solution set. The current solution is represented as S = {"Red"}.
7. Objective Function
   At this stage, an evaluation is conducted to determine whether all vertices have been colored with an optimal solution. If all vertices are successfully colored, the process terminates. However, if there are still uncolored vertices, the procedure returns to the vertex selection step. Since only vertex v_{22} has been colored, the process continues with the selection of the next vertex.
8. Vertex Selection Step for v_3
   The next vertex selected for coloring is v_3 as it has the second-highest degree along with v_6,v_{19}, and v_{30}. The red color from the solution set is considered for this vertex. By examining the adjacency of vertex v_3, it is confirmed that none of its neighboring vertices are assigned the red color. Therefore, vertex v_3 can also be colored red. Subsequently, the red color is retained in the solution set, represented as S = {"Red"}. The graph coloring process is illustrated in Figure 5.

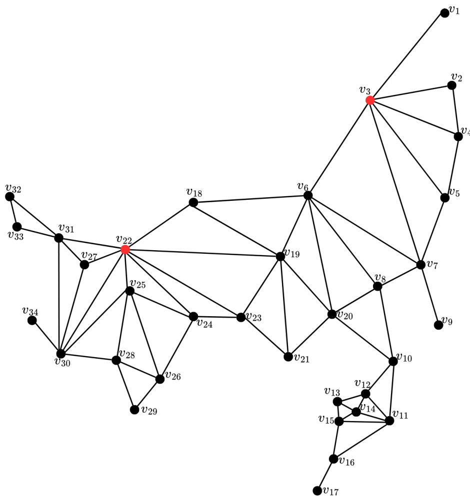

Figure 5. Coloring in Vertex v_3

9. Next Vertex Selection Step
   The color selection process is carried out iteratively for each vertex, starting from the vertex with the highest degree and continuing to the next vertex that meets the criteria. The coloring proceeds until all vertices in the graph are assigned a color, ensuring that no two adjacent vertices share the same color. The final result of the graph coloring process is presented in Figure 6.

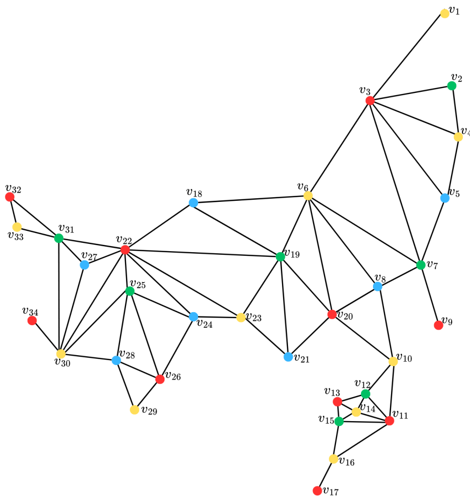

Figure 6. Final Result Of Graph Coloring

10. Objective Function
    The coloring process is terminated once all vertices have been assigned colors, with the final solution set expressed as $S = \{\text{Red,Yellow,Green,Blue}\}$.

After applying the Greedy Algorithm to the graph coloring of the Kalimantan map along with its regional labels, the chromatic number, or the minimum number of colors required, is determined to be four, as illustrated in Figure 7.

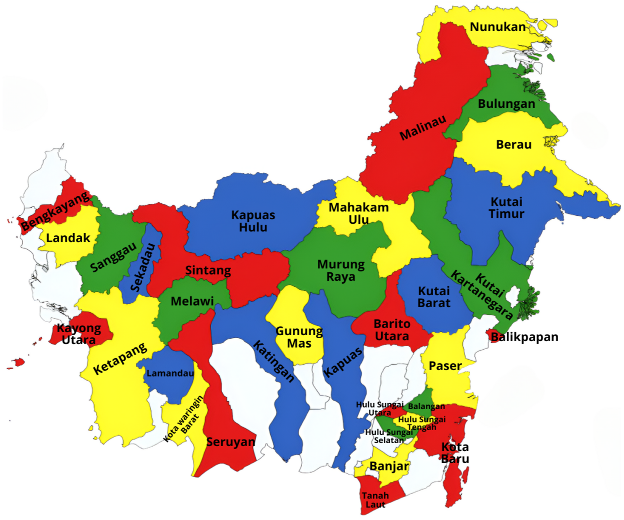

Figure 7. Graph Coloring On The Kalimantan Map With Regional Names

DISCUSSION

The application of the Greedy Algorithm in coloring the map of primary dryland forest cover in Kalimantan Province demonstrates that this approach is effective in ensuring that adjacent regions do not share the same color. Representing the regions as a graph allows the coloring process to be carried out systematically, particularly by prioritizing vertices with the highest degree. In this way, color distribution can be optimized. The results indicate that four colors are sufficient to color all regions without any conflict between neighboring areas. This finding aligns with the concept of the chromatic number in graph theory, which states that planar maps can be colored with a minimal number of colors. The use of this algorithm not only provides an efficient solution but also offers practical applications in areas such as regional clustering, spatial planning, and geographic information systems.

CONCLUSION

The findings of this study indicate that the Greedy Algorithm can be applied to color the map of primary dryland forest cover in Kalimantan, ensuring that adjacent regions do not share the same color. The coloring process was carried out by representing regions as a graph and applying the coloring rules based on the ordering of vertices with the highest degree. The results of graph coloring using the Greedy Algorithm show that the minimum number of colors required to color the graph, where each neighboring region is assigned a different color, is the chromatic number $\chi(G) = 4$. This ensures that no two adjacent regions share the same color, thereby achieving an optimal map coloring.

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The authors declare that generative AI or AI-assisted technologies were not used in any way to prepare, write, or complete this manuscript. The authors confirm that they are the sole authors of this article and take full responsibility for the content therein, as outlined in COPE recommendations.

INFORMED CONSENT

The authors have obtained informed consent from all participants.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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