Spatial Analysis of Artificial Forest Success Rates and Their Role in Carbon Sequestration in the Kurdistan Region of Iraq

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Abstract

This study assesses the spatial distribution and success rates of artificial forests established between 1973 and 2013 in the Kurdistan Region of Iraq, focusing on the provinces of Erbil, Duhok, Sulaymaniyah, and Halabja. A total of 541 georeferenced sites, covering 23,034.2 hectares, were evaluated through field surveys and geographic information system (GIS) analysis to determine current forest cover relative to the total area afforested. Results reveal significant inter-provincial variation in survival rates: Duhok recorded the highest forest cover at 50.1%, followed by Halabja (46.2%), while Sulaymaniyah (27.9%) and Erbil (27.4%) had substantially lower success rates. Spatial patterns show that high-survival sites cluster predominantly in mountainous areas with favorable climatic and edaphic conditions, whereas low-survival sites are concentrated in lowland zones affected by overgrazing, land conversion, and inadequate post-planting care. The findings highlight the critical influence of microclimate, site selection, and management practices on plantation success, underscoring the need for targeted reforestation strategies that prioritize degraded areas while enhancing protection in high-survival zones. Forested areas across Erbil, Duhok, Sulaymaniyah, and Halabja provinces were analyzed to estimate total biomass production (TBP), carbon stored in dry matter, and corresponding CO_2 equivalents. Remote sensing estimates showed a cumulative TBP of 11.06 billion kg dry matter annually, equivalent to 4.98 billion kg of carbon and 18.26 million tonnes of CO_2 . Field sampling across 13 plots revealed significant heterogeneity in aboveground biomass and carbon storage, driven largely by tree diameter, stand density, and site conditions. Dry weight per hectare ranged from 480.9 kg to 39,692.1 kg, while carbon storage varied between 1.44 $t \cdot ha^{-1}$ and 238.15 $t \cdot ha^{-1}$. High-performing plots with larger tree diameters and higher stand densities disproportionately contributed to total carbon stocks, confirming the critical role of site conditions and forest management in biomass accumulation. These findings underscore the importance of targeted silvicultural practices and sustainable forest management to enhance the carbon sequestration potential of KRI's forests, contributing to regional and global climate change mitigation efforts.

Keywords: Artificial forests, afforestation success rate, GIS analysis, spatial distribution, Total biomass production (TBP), Carbon Sequestration, and Kurdistan Region, Iraq,

1- Introduction

Forest is defined as a land that covers more than 0.5 hectares with trees higher

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than 5 meters and their crowns cover more than 10% [1]. Forest trees are a crucial component of the Earth's ecosystems, playing a significant role in maintaining biodiversity, regulating the climate, and supporting human livelihoods [2].These trees exist in both natural and artificial forests, covering approximately 31% of the planet's land area they provide oxygen, store carbon, and serve as habitats for countless species of flora and fauna [3]. Beyond their role in climate regulation, forest trees support a vast range of species, providing shelter and food for countless animals, plants, and microorganisms. These trees contribute to the rich biodiversity found in forests, which is vital for ecosystem resilience and the health of the planet. Forests also regulate water cycles, prevent soil erosion, and purify the air by filtering pollutants [4]. Natural forests around the world are irreplaceable ecosystems that have evolved over millennia, providing critical environmental services that sustain life on Earth [5]. Globally, natural forests are essential for maintaining the health of the planet [6]. They regulate the climate by absorbing and storing large amounts of carbon dioxide, one of the key greenhouse gases responsible for climate change[7]. Through the process of photosynthesis, trees in natural forests produce oxygen and remove pollutants from the air, making them vital for air quality [3]. In addition, natural forests are crucial in regulating the global water cycle. They play a key role in maintaining rainfall patterns, filtering and storing water, and preventing soil erosion [8]. Globally, artificial forests play an important role in meeting the growing demand for forest products while reducing pressure on natural forests while artificial forests may not support the same complexity or variety of species as natural forests, they are an important tool in sustainable land use and resource management, particularly in regions where deforestation and land degradation are significant concerns [9].By providing resources such as timber, paper, and other wood products, plantation forests help minimize the need for logging in ecologically sensitive areas, thus contributing to the preservation of biodiversity in natural forests[10]. Forest trees play a crucial role in global carbon sequestration, which is the process by which carbon dioxide (CO_2) is captured from the atmosphere and stored in organic material, primarily in trees and soil [11]. This process is vital for mitigating climate change by reducing the overall concentration of CO_2 , a major greenhouse gas [12]. Trees absorb CO_2 from the atmosphere during photosynthesis. Through this natural process, trees use sunlight to convert CO_2 into glucose, which is stored in their roots, trunks, branches, and leaves. As a result, forests act as significant carbon sinks [13]. On a global scale, forests absorb around 7.6 billion metric tons of CO_2 annually, which accounts for nearly one-third of all anthropogenic emissions caused by human activities [14]. Forests collectively store about 289 gigatonnes (Gt) of carbon in their biomass and soils. This is more than three times the amount of carbon in the atmosphere (Nesha, 2021).

In Iraq, forest trees are an essential part of the ecosystem, though forests are relatively limited due to the country's predominantly arid and semi-arid climate[16]. The forested areas of Iraq are concentrated in the northern and northeastern regions, particularly in the mountainous areas of the Kurdistan Region. These forests are home to a variety of tree species, each playing a crucial role in the country's ecological balance [17]. In Iraq, both natural forests and artificial forests are vital to the country's environmental stability. Natural forests, though limited, are crucial for biodiversity, soil conservation, and carbon storage[18]. On the other hand, artificial forests have been established to address environmental degradation and provide necessary resources to local communities [19]. Efforts to preserve and expand forested areas in Iraq are critical in the fight against desertification, climate change, and the ongoing challenges posed by human activity on the landscape [20]. In Iraq, where the climate is predominantly arid and semi-arid, forests are limited, yet their role in carbon sequestration remains significant, especially in the northern and northeastern regions, such as the Kurdistan Region In Iraq, the importance of forest trees in carbon sequestration extends beyond their environmental benefits [21]. The preservation and expansion of Iraq’s forested areas can contribute to the country's efforts to combat desertification and land degradation, both of which are exacerbated by climate change. However, the loss of Iraq's forests due to deforestation, illegal logging, overgrazing, and the impacts of climate change poses a significant threat to the ability of forest ecosystems to sequester carbon Efforts to protect, restore, and sustainably manage these forests are essential to enhancing carbon storage capacity and ensuring long-term environmental stability in Iraq [22]. In addition to their ecological importance, the forests of Kurdistan have cultural significance [19]. Many of the tree species found in these forests are integral to local traditions and the economy, as they provide resources for timber, fuel, and even food, such as pistachio nuts from pistachio trees (Pistacia vera) furthermore, the forests are crucial in the fight against climate change, as they help sequester carbon and stabilize the environment [23]. Despite their importance, the forests of Kurdistan are facing significant challenges, such as deforestation, overgrazing, and the impacts of climate change, including droughts and increasing temperatures. Efforts to conserve and sustainably manage these forests are essential for preserving their ecological, economic, and cultural value [24]. Natural forests in Kurdistan are primarily found in the mountainous areas of the region, where the climate ranges from temperate to Mediterranean. These forests are characterized by a variety of tree species, such as oak, pine, juniper, and fir, alongside diverse flora and fauna. Kurdistan's natural forests have developed over centuries without human intervention, maintaining a delicate balance that supports wildlife, provides essential ecosystem services, and contributes to the livelihoods of local communities who rely on them for fuelwood, timber, and medicinal plants [25]. Artificial forests, also known as man-made or plantation forests, are an essential tool for addressing various environmental challenges, particularly in regions facing deforestation, soil erosion, and biodiversity loss. In Kurdistan, a region rich in natural landscapes and biodiversity, the

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introduction of artificial forests has gained significant attention as a strategy to combat land degradation, improve air quality, and promote sustainable land use practices Artificial forests in Kurdistan are typically created by planting fast-growing tree species, such as poplar, pine, and eucalyptus, in areas that were once deforested or where natural forest regeneration is difficult. These forests serve multiple purposes, including reducing soil erosion, providing timber and non-timber forest products, improving water retention in the soil, and enhancing the overall climate resilience of the region [26]. However, the success of artificial forest initiatives in Kurdistan depends on factors such as careful selection of tree species, proper management practices, and the integration of these projects into broader environmental and socioeconomic strategies. Despite the benefits, challenges remain in ensuring the sustainability and long-term viability of artificial forests in the region [27].

Forests in the Kurdistan Region of Iraq play a crucial role in climate change mitigation through carbon sequestration as carbon sinks, forests absorb and store carbon dioxide from the atmosphere, helping to regulate the global carbon cycle and reduce the impact of greenhouse gas emissions [28]. The unique biodiversity and geographical features of Kurdistan’s forests, particularly those in protected areas, enhance their capacity to sequester carbon with increasing deforestation and land degradation, it is essential to understand and monitor the carbon storage potential of these forests [29].

Based on what were mentioned, this study aims to:
This study is expected to yield significant results as I am working on the assessment of natural forests, the evaluation of artificial forests, and the calculation of carbon sequestration in forested areas. I am the first to distinguish between natural and artificial forests in the regions of Sulaymaniyah, Duhok, and Erbil. Additionally, I will assess the natural protected areas and explore ways to enhance participation in carbon sequestration efforts.

2. Materials and Methods

2.1. Study Area

The KRI territories were selected as the study area in this research, particularly in Erbil, Sulaimaniyah, and Duhok governorates. The study area is located in the northern part of Iraq Syria borders the study area from the west, Iran from the east, and Turkey from the north, which is cold and rainy in winter and hot and dry in summer It is situated between latitudes 34° and 37° and longitudes 41° and 46°, covering an extent of about 53,000 km2, which constitutes a large portion of the entire Iraq territory it has a diverse physical environment, whereas the elevation ranges from 88 m in its southern parts to more than 3603 m in the north and northeast parts [30]. The protected areas in the Kurdistan Region of Iraq for this study the first one is we have Zawita in Duhok governorate, Safeen Mountain in Erbil governorate, Qaradagh Mountains in the

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Sulaymaniyah Governorate,and Mergasur in Barzan (Erbil governorate).

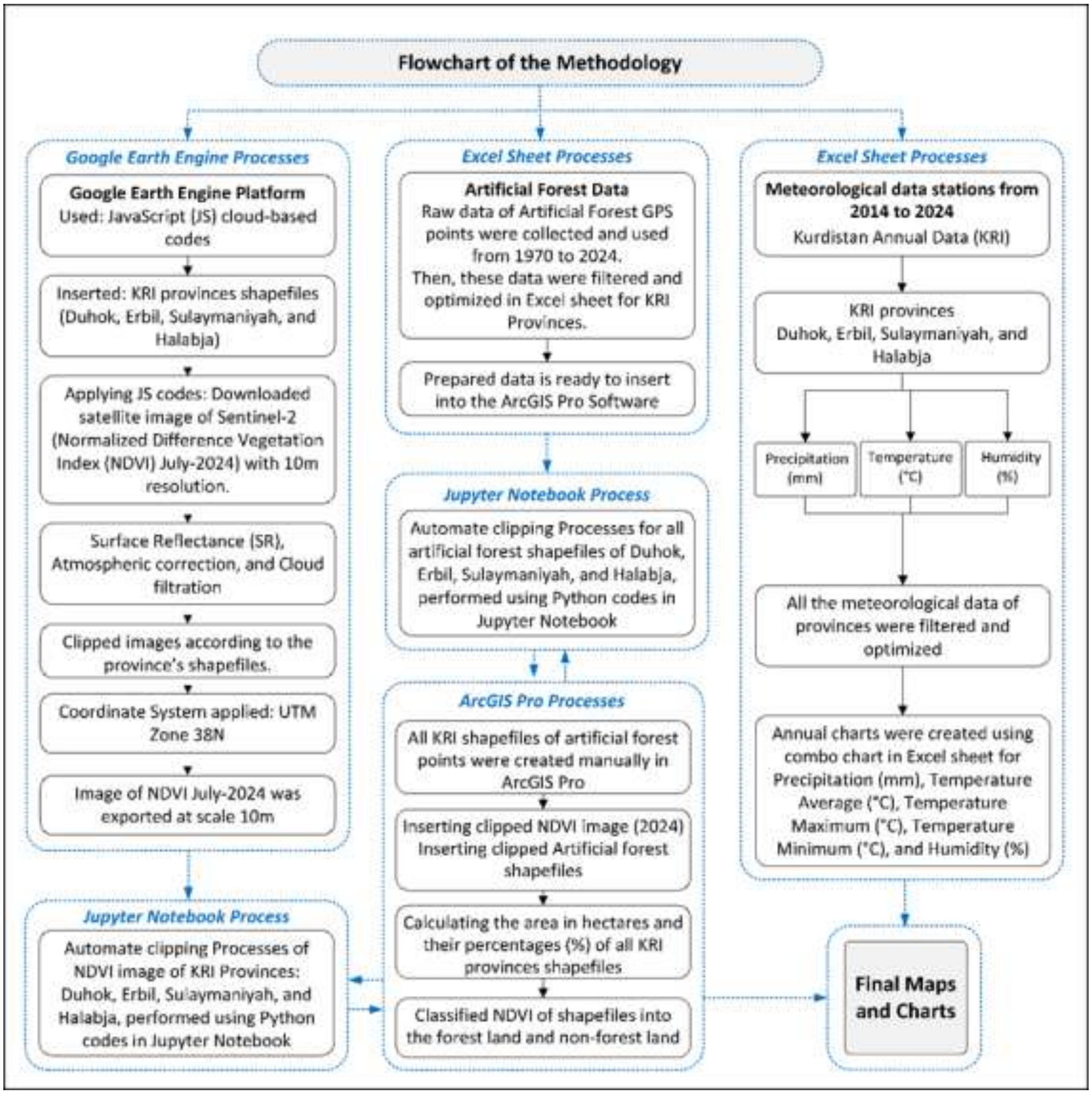

Figure 1. The flow chart of the study methodology.

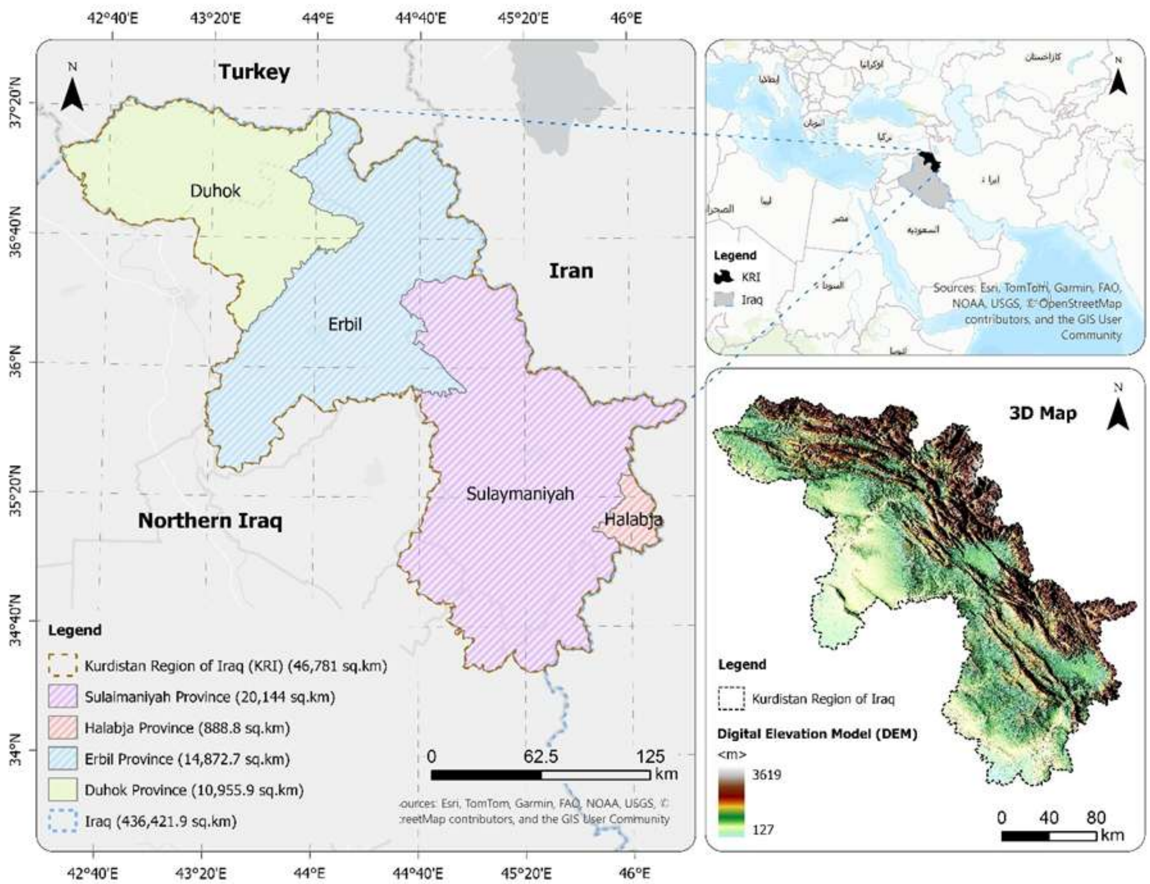

Figure 2. Map of Iraq Kurdistan Region, Digital Elevation Map (DEM) Raster.

2.2 Geographic and Ecological Characteristics of the Protected Natural Forest Areas in The Kurdistan Region.

This study focuses on selected protected natural forest areas within the Kurdistan Region of Iraq, located in the northeastern part of the country, bounded approximately between 35° to 38° N latitude and 43° to 47° E longitude.

The region includes the governorates of Duhok, Erbil, and Sulaymaniyah, and forms part of the larger Zagros Mountain range, which extends into western Iran and southeastern Turkey [31]. The Zagros forests are considered ecologically significant due to their rich biodiversity and role in regulating the regional climate and hydrology [32]

2.3. Data Collection

2.3.1. Satellite Data Sources

Satellite imagery plays a critical role in assessing forest cover, vegetation dynamics, and ultimately estimating the carbon sequestration potential of forest ecosystems. In this study, three main

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satellite sources were utilized: Landsat, Sentinel-2, and MODIS, selected for their complementary spatial and temporal resolutions.

Landsat imagery offers 30-meter spatial resolution across several spectral bands, with a 16-day revisit frequency. This medium-resolution data is ideal for long-term monitoring of forest cover and detecting land cover changes [33]. Sentinel-2 provides high-resolution data (10-20 meters) with 13 spectral bands and a 5-day revisit cycle when both Sentinel-2A and 2B are considered. This high temporal frequency enables detailed monitoring of vegetation dynamics, particularly in terms of vegetation indices such as NDVI, which are closely linked to biomass and carbon sequestration [34].

2.3.2. *GIS Data* **Land Cover and Land Use Maps**:

These maps are essential for identifying forest types, vegetation cover, and land-use changes, which directly affect carbon sequestration capacity. Remote sensing tools such as Landsat and MODIS help track deforestation and land-use changes, providing insights into areas with high carbon storage potential [35].

2.3.3. Climatic data (e.g., temperature, rainfall) relevant to carbon sequestration

Climatic conditions, particularly temperature and precipitation, are critical variables influencing carbon sequestration processes in forest ecosystems. In the Kurdistan Region of Iraq, the Mediterranean climate dominates, characterized by hot, dry summers and mild, wet winters according to data from the Iraqi Meteorological Organization and Seismology average annual rainfall in the region ranges between 400 to 1000 mm, with most precipitation occurring between November and March [36]. climatic patterns directly affect vegetation growth, soil moisture content, and consequently, the rate at which carbon is sequestered by forest biomass and soils. Remote sensing data, when integrated with long-term climate records, provide a reliable foundation for modelling spatial and temporal variations in carbon sequestration furthermore, the Intergovernmental Panel on Climate Change [37].

Figure 3 Yearly precipitation, relative humidity, actual evaporation, maximum, minimum, and mean temperature recorded from 2014 to 2023.

3. Results and Discussion

Table 4.1 presents the distribution of artificial forest areas across the four provinces of the Kurdistan Region of Iraq from 1970 to 2013. The total area of artificial forests established during this period amounts to 12,506.6 hectares.

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Duhok province recorded the largest share, with 4,668.5 hectares, representing 37.3% of the total artificial forest area. This dominance may be attributed to the province's favorable topographic and climatic conditions, as well as active reforestation initiatives during the study period. Sulaymaniyah follows with 4,223.3 hectares (33.8%), reflecting significant afforestation efforts, possibly due to the province’s mountainous terrain and government or community-led forestation programs aimed at combating land degradation and soil erosion. Erbil province

accounts for 2,978.4 hectares (23.8%), indicating moderate afforestation activity. While the province possesses suitable ecological conditions in some areas, competing land uses such as agriculture and urban expansion may have limited the scale of artificial forest establishment. Halabja recorded the smallest area of artificial forests, with 636.5 hectares (5.1%). The limited extent may be linked to the province’s smaller geographical size and socio-political challenges, particularly in the decades preceding its administrative recognition as a separate province.

Overall, the results show an uneven spatial distribution of artificial forest areas, with more than 70% concentrated in Duhok and Sulaymaniyah. This suggests that reforestation strategies have been more intensive in the northern and eastern highland areas, likely due to environmental priorities and land suitability.

Table 1. Area of artificial forest in Iraq Kurdistan region1970-2013.

Province	Area (hectare)	%
Duhok	4668.5	37.3
Erbil	2978.4	23.8
Sulaymaniyah	4223.3	33.8
Halabja	636.5	5.1
SUM	**12506.6**	**100**

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Table 2

. Percentage of successful artificial forests based on the total area afforested between 1973 and 2013 in Erbil province.

Erbil Locations	X	Y	Non-Forest Area (ha)	%	Forest Area (ha)	%
E000	44.501449	36.646638	2.12	49.5	2.16	50.5
E001	44.537490	36.632399	2.13	61.4	1.34	38.6
E002	44.528970	36.642369	3.23	20.2	12.77	79.8
E003	44.559710	36.663922	4.03	100.0	0	0.0
E004	44.556209	36.666678	1.68	61.5	1.05	38.5
E005	44.559385	36.649708	2.71	24.5	8.35	75.5
E006	44.182121	36.220709	119.23	87.0	17.88	13.0
E007	44.633895	36.629551	1.41	31.5	3.06	68.5
E008	44.013769	36.221787	20.86	100.0	0	0.0
E009	44.113219	36.163874	17.31	100.0	0	0.0
E010	44.111306	36.162647	19.02	100.0	0	0.0
E011	44.091604	36.164510	9.98	100.0	0	0.0
E012	44.092517	36.164990	9.56	100.0	0	0.0
E013	44.202961	36.035901	192.3	97.4	5.08	2.6
E014	44.213321	36.042666	25.44	92.7	2	7.3
E015	44.827080	36.608981	24.31	65.3	12.89	34.7
E016	44.879103	36.626394	4.43	33.0	9	67.0
E017	44.878953	36.631793	6.33	54.0	5.39	46.0
E018	44.892455	36.646376	0.4	37.7	0.66	62.3
E019	43.834456	35.909261	22.18	100.0	0	0.0
E020	43.833835	35.905759	15.48	100.0	0	0.0
E021	44.386546	36.181714	7.9	80.5	1.91	19.5
E022	44.382648	36.178084	3.5	92.1	0.3	7.9
E023	44.347559	36.561529	1.97	59.9	1.32	40.1
E024	44.350324	36.543296	6.5	82.6	1.37	17.4
E025	44.375370	36.431901	15.92	97.4	0.42	2.6
E026	44.380252	36.433974	48.21	82.2	10.47	17.8
E027	44.384815	36.456393	0.53	100.0	0	0.0
E028	44.370544	36.488347	29.72	53.1	26.2	46.9
E029	44.490190	36.689703	6.78	61.0	4.34	39.0
E030	44.496212	36.276413	0.67	14.6	3.91	85.4
E031	44.198917	36.223135	21.8	86.2	3.5	13.8
E032	44.156834	36.214803	9.39	99.9	0.01	0.1
E033	44.166808	36.211745	53.95	95.2	2.7	4.8
E034	44.192056	36.217491	23.58	63.5	13.56	36.5
E035	44.658375	36.089146	48.42	77.7	13.93	22.3
E036	44.660167	36.099976	105.55	80.5	25.58	19.5
E037	44.666061	36.106279	38.5	52.0	35.52	48.0
E038	44.564595	36.074421	30.09	98.0	0.62	2.0
E039	44.216762	36.391853	111.94	56.7	85.44	43.3
E040	44.184783	36.355169	12.3	82.1	2.69	17.9

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E041	44.280858	36.391488	3.54	9.6	33.48	90.4
E042	44.182974	36.356725	0.25	22.5	0.86	77.5
E043	43.590971	35.761326	9.88	100.0	0	0.0
E044	43.595435	35.762254	14.17	100.0	0	0.0
E045	44.204653	36.893724	19.04	44.9	23.34	55.1
E046	44.542433	36.613015	229.57	62.0	140.47	38.0
E047	44.023369	36.113471	4.34	100.0	0	0.0
E048	43.918667	36.183025	2.54	100.0	0	0.0
E049	43.910509	36.189089	8.89	100.0	0	0.0
E050	43.905468	36.193056	4.47	100.0	0	0.0
E051	44.660296	36.809779	6.19	49.0	6.45	51.0
E052	44.337208	36.407173	30.58	74.3	10.58	25.7
E053	44.313658	36.418244	26.4	68.6	12.06	31.4
E054	44.321598	36.402109	10.68	49.9	10.72	50.1
E055	44.355623	36.395678	52.13	62.0	31.95	38.0
E056	44.267970	36.400311	20.46	18.3	91.18	81.7
E057	44.594244	35.905194	11.16	100.0	0	0.0
E058	43.644998	36.256434	41.42	100.0	0	0.0
E059	43.646597	36.265813	5.77	100.0	0	0.0
E060	43.651005	36.268667	14.26	100.0	0	0.0
E061	43.650267	36.265702	6.57	100.0	0	0.0
E062	43.645638	36.261805	28.65	100.0	0	0.0
E063	43.673709	36.267675	35.76	100.0	0	0.0
E064	43.684271	36.263847	7.71	100.0	0	0.0
E065	43.655042	36.270626	1.07	100.0	0	0.0
E066	43.865571	36.211024	1.46	98.6	0.02	1.4
E067	43.906686	36.187453	0.87	60.4	0.57	39.6
E068	43.983591	36.191114	100.33	46.3	116.19	53.7
E069	44.013089	36.218059	6.49	99.5	0.03	0.5
E070	44.032999	36.228483	120.41	99.9	0.08	0.1
E071	44.047624	36.196921	7.11	97.8	0.16	2.2
E072	44.040354	36.194805	0.94	94.9	0.05	5.1
E073	44.016575	36.199081	5.47	99.1	0.05	0.9
E074	44.002562	36.181670	8.2	46.6	9.4	53.4
E075	44.009056	36.182733	6.25	66.6	3.14	33.4
E076	43.999284	36.179165	7.87	78.3	2.18	21.7
E077	44.000556	36.185698	4.34	51.1	4.15	48.9
E078	44.019373	36.171844	5.91	84.3	1.1	15.7
E079	44.045568	36.170823	4.13	100.0	0	0.0
E080	44.027922	36.152163	3.73	100.0	0	0.0
E081	43.984307	36.178259	1.59	98.8	0.02	1.2
E082	43.984574	36.181450	2.38	96.7	0.08	3.3
E083	44.000861	36.213757	9.42	100.0	0	0.0
E084	44.003960	36.232362	6.95	99.6	0.03	0.4
E085	44.000334	36.234962	2.46	99.6	0.01	0.4
E086	44.080998	36.257863	16.26	99.7	0.05	0.3
E087	43.971000	36.110037	4.85	100.0	0	0.0
E088	44.015750	36.129975	4.44	100.0	0	0.0
E089	44.011322	36.129893	4.06	100.0	0	0.0

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E090	44.095463	36.260887	4.6	98.3	0.08	1.7
E091	44.099728	36.262734	19.26	96.1	0.78	3.9
E092	44.107737	36.261768	11.41	95.3	0.56	4.7
E093	44.022305	36.255884	13.76	100.0	0	0.0
E094	44.047332	36.149716	1.91	100.0	0	0.0
E095	44.050646	36.153108	1.35	100.0	0	0.0
E096	44.043163	36.146147	1.94	100.0	0	0.0
E097	44.044748	36.144951	1.83	100.0	0	0.0
E098	44.046990	36.146625	0.72	100.0	0	0.0
E099	44.072343	36.176947	15.51	100.0	0	0.0
E100	43.991053	36.239701	6.63	100.0	0	0.0
E101	44.052206	35.970451	21.14	100.0	0	0.0
E102	44.011831	36.188387	0.18	25.7	0.52	74.3
E103	44.012371	36.196830	0.42	100.0	0	0.0
E104	44.023019	36.191647	0.8	100.0	0	0.0
E105	44.028311	36.193907	0.37	100.0	0	0.0
E106	44.027429	36.154547	0.57	70.4	0.24	29.6
E107	44.028510	36.156480	0.63	100.0	0	0.0
E108	44.026648	36.156510	0.16	100.0	0	0.0
E109	44.032826	36.161838	0.95	100.0	0	0.0
E110	44.042957	36.151969	0.54	100.0	0	0.0
E111	44.042428	36.150941	0.5	100.0	0	0.0
E112	44.044913	36.153584	0.47	87.0	0.07	13.0
E113	44.054851	36.159174	1.99	100.0	0	0.0
E114	44.053281	36.160461	0.52	100.0	0	0.0
E115	44.050300	36.159923	1.05	100.0	0	0.0
E116	44.038644	36.159180	0.43	100.0	0	0.0
E117	44.036370	36.159031	0.41	100.0	0	0.0
E118	44.032142	36.158267	4.44	94.3	0.27	5.7
E119	44.043417	36.159472	1.23	100.0	0	0.0
E120	44.058667	36.160491	1.79	100.0	0	0.0
E121	44.070455	36.161322	1.84	100.0	0	0.0
E122	44.078831	36.163809	2.29	100.0	0	0.0
E123	44.091279	36.158573	25.31	99.9	0.02	0.1
E124	44.081156	36.162092	1.75	100.0	0	0.0
			2161.5	%**72.6**	**816.4**	%**27.4**

3.1. Erbil Province Case Study

The detailed spatial assessment in Erbil Province, covering 125 georeferenced locations, revealed that forest cover is limited compared to non-forest areas. The total surveyed area amounted to 2,977.9 ha, of which 2,161.5 ha (72.6%) was classified as non-forest, while only 816.4 ha (27.4%) was covered by forest. This indicates that, although Erbil contributes 23.8% of the total artificial forest area in the Kurdistan Region, its forest cover remains spatially fragmented and generally surrounded by non-forested land uses. The distribution of forest cover across surveyed locations was highly variable. Some sites, such as E002, E005, E041, and E056, recorded forest coverage above 75%, suggesting effective afforestation or the presence of well-preserved stands. In contrast, a

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substantial number of sites, including E003, E008–E012, E019–E020, E027, E043–E044, and E057–E066, showed **0% forest cover**, indicating a complete absence of forest vegetation. Additionally, several sites such as E068, E074, E046, and E039 exhibited mixed land cover, with significant portions of both forest and non-forest areas, reflecting partially degraded or regenerating landscapes.

Spatially, forested areas tend to occur in clusters, often in locations benefiting from favorable microclimates, targeted plantation programs, or proximity to protected reserves. In contrast, deforested and degraded sites are more widely dispersed, frequently located near agricultural fields, urban expansion zones, or regions subject to overgrazing and logging activities. This spatial pattern highlights the combined influence of environmental suitability and anthropogenic pressures on forest distribution. The relatively low forest percentage in Erbil compared to Duhok (37.3%) and Sulaymaniyah (33.8%) suggests multiple challenges. These include intensive land conversion for agriculture and settlements, unsustainable fuelwood extraction, inadequate maintenance and follow-up of plantation sites, and ecological limitations in semi-arid lowland areas. Addressing these issues requires a targeted restoration strategy that focuses on areas with the lowest forest cover, while strengthening protection measures for high-cover zones. Integrating these field observations with GIS-based spatial prioritization could help create ecological corridors, enhance forest connectivity, and improve the resilience of artificial forests in the province.

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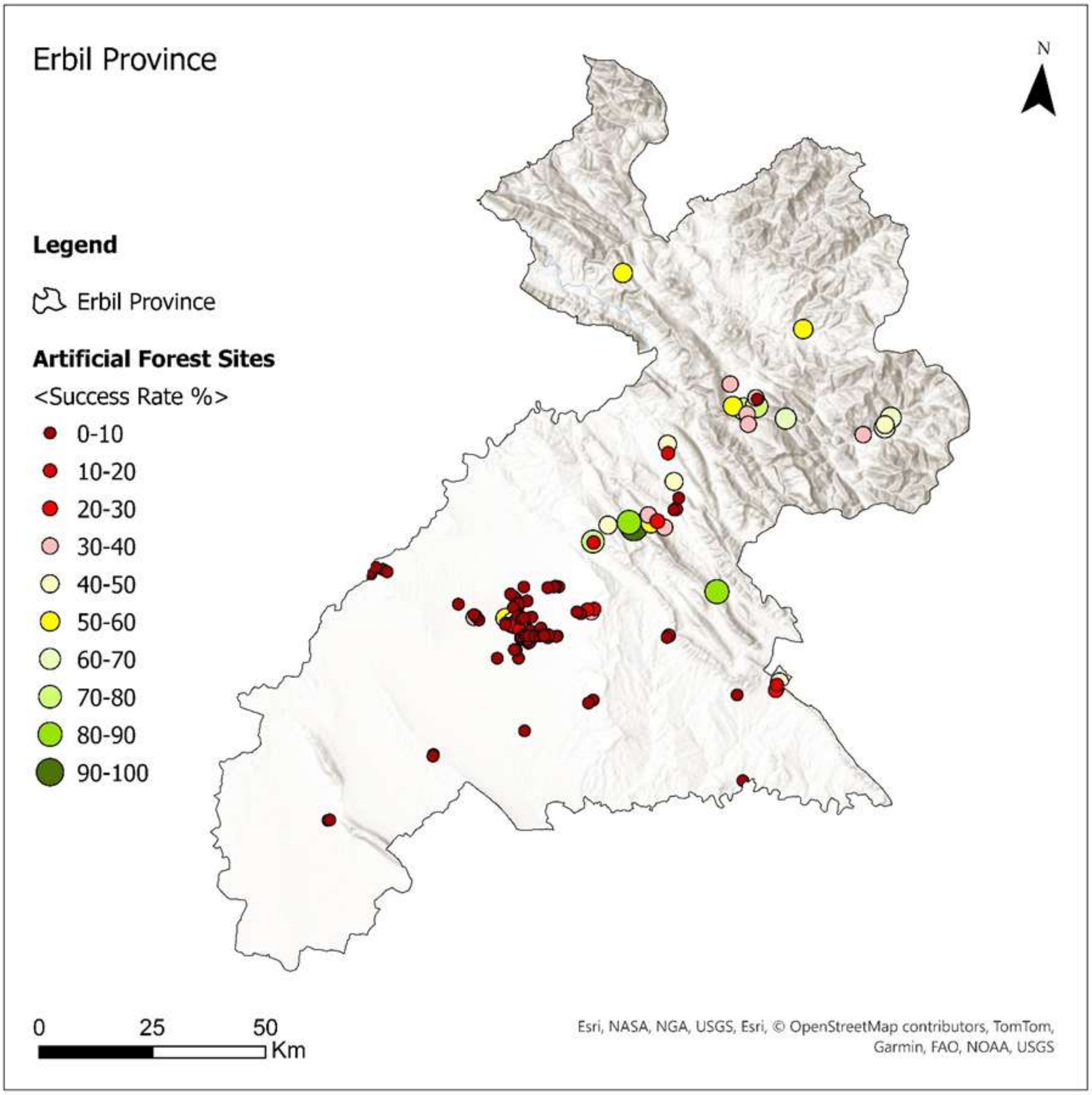

Figure 4. The spatial distribution of the Map of Success rate of artificial forest based on the total area afforested between 1973 and 2013.

3.2. Duhok Province Case Study

The analysis of 229 artificial forest sites in Duhok Province, covering a total surveyed area of 4,667.6 ha, revealed a nearly balanced distribution between forest and non-forest land. Forested areas accounted for 2,337.8 ha (50.1%), while non-forest areas made up 2,329.8 ha (49.9%). This indicates that, compared to other provinces in the Kurdistan Region, Duhok has achieved a relatively high proportion of successful afforestation, aligning with its overall contribution of 37.3% to the region's total artificial forest area. The dataset

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highlights considerable variation in forest success rates across sites. High-performing sites, such as D065, D067, D070–D072, D077–D083, D087, D090–D094, D101, D103, D108, D217, and D228, exhibited success rates above 85%, with some exceeding 95%. These locations likely benefited from favorable ecological conditions, including higher precipitation, suitable soils, and effective site management. In contrast, a substantial number of sites recorded 0–10% forest cover (e.g., D000–D007, D009–D011, D013, D138–D141, D144–D147, D175, D178–D186), indicating plantation failure or complete forest loss, potentially due to poor site selection, drought stress, overgrazing, or anthropogenic disturbances. Spatially, high-success zones appear to be concentrated in the southeastern and central mountainous areas of the province, whereas low-success sites are more frequent in the southwestern lowlands and along certain valley areas. This distribution pattern suggests that topography and microclimate play critical roles in afforestation outcomes, with upland areas offering better conditions for seedling establishment and long-term survival.

The overall 50.1% success rate in Duhok is notably higher than that recorded in Erbil (27.4%) and is slightly above the average for the Kurdistan Region. This can be attributed to historical afforestation policies, the province's ecological suitability, and possibly stronger protection measures in forested areas. However, the persistence of large areas with minimal or no forest cover indicates that management challenges remain. Targeted interventions such as replanting in failed sites, controlling grazing, improving irrigation during establishment, and applying soil conservation techniques could further enhance forest cover in the province.

Table 3

. Percentage of successful artificial forests based on the total area afforested between 1973 and 2013 in Duhok province

Duhok Locations	X	Y	Non-Forest Area (ha)	%	Forest Area (ha)	%
D000	43.76861	36.67776	1.3	100.0	0.0	0.0
D001	43.76245	36.67323	2.8	100.0	0.0	0.0
D002	43.77500	36.68247	1.6	100.0	0.0	0.0
D003	43.77934	36.68558	0.6	100.0	0.0	0.0
D004	43.78238	36.68775	0.8	100.0	0.0	0.0
D005	43.78541	36.69000	1.0	100.0	0.0	0.0
D006	43.78898	36.69258	0.7	100.0	0.0	0.0
D007	43.79485	36.69685	3.4	100.0	0.0	0.0
D008	43.80337	36.70309	2.0	99.0	0.0	1.0
D009	43.80779	36.70631	0.2	100.0	0.0	0.0

D010	43.80897	36.70713	0.3	100.0	0.0	0.0
D011	43.81536	36.71179	3.5	99.7	0.0	0.3
D012	43.82187	36.71644	0.6	90.9	0.1	9.1
D013	43.82423	36.71826	0.7	100.0	0.0	0.0
D014	43.86444	36.73225	6.0	65.9	3.1	34.1
D015	43.87882	36.75076	30.9	67.7	14.8	32.3
D016	43.88016	36.76156	84.1	61.2	53.3	38.8
D017	43.90214	36.74366	54.4	75.0	18.2	25.0
D018	43.90381	36.74857	2.5	98.1	0.1	1.9
D019	43.91163	36.74513	7.5	62.2	4.6	37.8
D020	43.90097	36.73856	0.7	67.7	0.3	32.3
D021	43.90539	36.74056	3.6	47.1	4.1	52.9
D022	43.90517	36.75489	11.3	47.5	12.5	52.5
D023	43.90769	36.74885	3.3	100.0	0.0	0.0
D024	43.89049	36.73686	3.0	98.0	0.1	2.0
D025	43.89306	36.73459	3.9	57.2	2.9	42.8
D026	43.89150	36.72998	5.5	55.5	4.4	44.5
D027	43.98880	36.80281	1.5	26.5	4.1	73.5
D028	44.00556	36.72732	32.9	84.3	6.2	15.7
D029	44.01999	36.72076	1.8	22.5	6.1	77.5
D030	43.81858	37.01958	1.7	16.5	8.7	83.5
D031	43.79900	37.02849	6.4	35.3	11.7	64.7
D032	43.79762	37.03253	7.1	54.2	6.0	45.8
D033	43.78172	37.03587	8.0	69.5	3.5	30.5
D034	43.66910	37.05084	29.6	55.7	23.6	44.3
D035	43.51545	37.09470	22.1	82.5	4.7	17.5
D036	43.50851	37.09358	10.5	42.2	14.3	57.8
D037	43.50391	37.09142	7.3	41.6	10.2	58.4
D038	43.50037	37.09494	1.5	30.4	3.5	69.6
D039	43.49722	37.09646	1.3	30.8	2.9	69.2
D040	43.49767	37.09787	0.7	29.2	1.7	70.8
D041	43.50026	37.10077	2.2	15.5	11.8	84.5
D042	43.49100	37.10410	17.4	71.6	6.9	28.4
D043	43.49259	37.09670	5.8	39.5	8.9	60.5
D044	43.49272	37.09202	6.3	55.0	5.2	45.0
D045	43.47501	37.10203	4.6	25.9	13.3	74.1
D046	43.47265	37.09931	3.7	45.4	4.4	54.6
D047	43.47339	37.09574	4.7	52.5	4.3	47.5
D048	43.45590	37.10070	0.7	44.9	0.9	55.1
D049	43.44769	37.09956	0.9	12.7	5.9	87.3
D050	43.44640	37.08976	2.2	31.9	4.8	68.1
D051	43.43259	37.09431	2.2	46.9	2.5	53.1
D052	43.43135	37.09317	1.2	38.9	1.9	61.1

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D053	43.42314	37.08941	0.5	15.3	2.5	84.7
D054	43.42133	37.08847	0.4	14.6	2.3	85.4
D055	43.41796	37.08775	1.8	35.9	3.3	64.1
D056	43.35405	37.09242	7.9	73.4	2.9	26.6
D057	43.35370	37.08793	20.8	67.3	10.1	32.7
D058	43.35020	37.08824	0.2	65.6	0.1	34.4
D059	43.34349	37.08547	6.6	26.7	18.2	73.3
D060	43.34007	37.07648	11.1	63.1	6.5	36.9
D061	43.33502	37.07606	7.7	74.3	2.7	25.7
D062	43.33460	37.07170	20.1	65.8	10.5	34.2
D063	43.34983	37.06608	46.8	47.6	51.5	52.4
D064	43.32290	37.04366	5.6	34.8	10.4	65.2
D065	43.32842	37.03977	20.9	16.9	102.8	83.1
D066	43.32287	37.03424	5.3	8.5	57.2	91.5
D067	43.30978	37.03100	1.3	2.8	45.8	97.2
D068	43.28370	37.03057	0.4	24.6	1.1	75.4
D069	43.27200	37.02882	2.3	22.1	8.2	77.9
D070	43.26092	37.02464	0.9	7.6	10.5	92.4
D071	43.25121	37.02525	0.3	6.3	4.8	93.7
D072	43.23853	37.02206	1.1	9.4	10.6	90.6
D073	43.26710	37.04262	4.0	30.9	9.0	69.1
D074	43.26227	37.04061	5.9	54.6	4.9	45.4
D075	43.22887	37.01089	6.6	24.4	20.4	75.6
D076	43.22349	37.01284	1.0	10.1	8.9	89.9
D077	43.21767	37.00373	14.2	12.0	104.1	88.0
D078	43.22363	37.00054	3.8	17.5	17.8	82.5
D079	43.21328	36.99147	1.5	27.6	4.0	72.4
D080	43.20923	36.98530	2.6	16.4	13.2	83.6
D081	43.21659	36.98234	5.1	10.3	44.3	89.7
D082	43.20342	36.97933	4.9	41.1	7.0	58.9
D083	43.20900	36.97510	1.9	8.9	19.0	91.1
D084	43.17748	36.96589	1.8	38.5	2.9	61.5
D085	43.16892	36.97008	1.7	25.7	4.8	74.3
D086	43.17189	36.95521	3.1	24.2	9.6	75.8
D087	43.16989	36.95114	0.1	4.6	1.5	95.4
D088	43.16303	36.94896	1.9	65.1	1.0	34.9
D089	43.12106	36.94016	3.4	45.6	4.1	54.4
D090	43.15231	36.92421	0.6	10.6	5.0	89.4
D091	43.14314	36.91940	4.6	11.9	34.4	88.1
D092	43.15304	36.91500	8.8	49.5	9.0	50.5
D093	43.16462	36.91361	5.5	9.7	51.0	90.3
D094	43.17075	36.92104	1.7	5.0	31.3	95.0
D095	43.14664	36.90923	3.4	33.8	6.6	66.2

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D096	43.13100	36.91057	20.1	21.5	73.4	78.5
D097	43.12094	36.91252	7.5	66.5	3.8	33.5
D098	43.12098	36.90850	7.2	33.0	14.6	67.0
D099	43.10662	36.90573	4.7	71.7	1.8	28.3
D100	43.12783	36.89926	41.0	68.1	19.2	31.9
D101	43.14761	36.90185	19.8	16.9	97.3	83.1
D102	43.13682	36.89894	21.5	45.5	25.8	54.5
D103	43.13318	36.89053	17.2	24.1	54.0	75.9
D104	43.12731	36.89290	15.7	52.8	14.0	47.2
D105	43.12208	36.88450	6.2	51.5	5.8	48.5
D106	43.12560	36.88424	7.4	27.8	19.2	72.2
D107	43.11961	36.87898	4.7	19.1	20.1	80.9
D108	43.12834	36.87372	4.3	8.4	47.0	91.6
D109	43.08848	36.91001	4.9	26.2	13.7	73.8
D110	43.07962	36.91192	21.0	48.2	22.6	51.8
D111	43.07417	36.90542	60.4	46.8	68.6	53.2
D112	43.05619	36.90747	13.1	60.8	8.4	39.2
D113	43.05304	36.91099	24.5	30.4	56.2	69.6
D114	43.04151	36.90535	44.7	45.1	54.4	54.9
D115	43.03254	36.91467	15.4	51.9	14.2	48.1
D116	43.02987	36.92225	15.4	48.7	16.2	51.3
D117	43.02243	36.91890	29.7	63.8	16.8	36.2
D118	43.01164	36.90103	94.0	63.1	55.1	36.9
D119	43.00329	36.93344	66.5	60.0	44.3	40.0
D120	42.99075	36.90280	60.6	59.8	40.7	40.2
D121	42.99477	36.88738	17.9	65.8	9.3	34.2
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D123	43.00383	36.87381	21.3	53.7	18.4	46.3
D124	42.99618	36.87182	4.9	82.0	1.1	18.0
D125	43.00679	36.86727	21.1	69.6	9.2	30.4
D126	43.02391	36.86109	9.8	55.7	7.8	44.3
D127	43.05608	36.85662	8.9	40.6	13.0	59.4
D128	43.05652	36.86327	42.6	64.0	24.0	36.0
D129	43.07127	36.86263	7.1	74.8	2.4	25.2
D130	43.06771	36.85806	13.5	33.7	26.6	66.3
D131	43.09287	36.86405	5.7	45.3	6.9	54.7
D132	43.09495	36.86736	7.6	33.7	14.9	66.3
D133	43.10342	36.87181	23.6	43.1	31.3	56.9
D134	42.93635	36.85848	13.2	88.6	1.7	11.4
D135	42.95782	36.84125	10.4	94.6	0.6	5.4
D136	42.88412	36.85042	22.8	88.9	2.9	11.1
D137	42.86416	36.85626	15.7	99.6	0.1	0.4
D138	42.82710	36.87468	3.0	100.0	0.0	0.0

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D139	42.82668	36.87681	1.5	100.0	0.0	0.0
D140	42.82239	36.87971	2.0	100.0	0.0	0.0
D141	42.82402	36.87949	2.2	100.0	0.0	0.0
D142	43.05846	36.96176	17.2	61.3	10.9	38.7
D143	43.44799	37.22830	5.7	82.2	1.2	17.8
D144	42.68522	36.96702	10.0	100.0	0.0	0.0
D145	42.65645	36.97181	0.3	100.0	0.0	0.0
D146	42.65695	36.97098	0.6	100.0	0.0	0.0
D147	42.64574	37.03241	3.1	100.0	0.0	0.0
D148	42.64451	37.04922	0.3	96.7	0.0	3.3
D149	42.64350	37.04932	0.6	100.0	0.0	0.0
D150	42.67605	37.12758	1.2	96.0	0.1	4.0
D151	42.67813	37.12836	0.3	59.6	0.2	40.4
D152	42.98577	37.17933	22.0	55.3	17.8	44.7
D153	43.01260	37.17967	7.6	43.5	9.9	56.5
D154	43.01800	37.18295	2.4	86.2	0.4	13.8
D155	43.02071	37.17695	6.5	57.5	4.8	42.5
D156	43.01653	37.19309	7.3	80.6	1.8	19.4
D157	43.01933	37.19126	8.3	92.0	0.7	8.0
D158	43.40642	36.93928	23.3	88.7	3.0	11.3
D159	43.34520	36.84915	76.6	49.8	77.3	50.2
D160	43.30267	36.80844	21.1	92.8	1.6	7.2
D161	43.50620	36.75789	35.0	98.3	0.6	1.7
D162	43.64013	36.27931	6.3	100.0	0.0	0.0
D163	43.62959	36.27094	11.0	100.0	0.0	0.0
D164	43.58285	36.48996	31.2	100.0	0.0	0.0
D165	43.58567	36.49586	127.2	99.2	1.0	0.8
D166	42.92417	36.79721	25.1	100.0	0.0	0.0
D167	42.92253	36.79722	28.7	99.9	0.0	0.1
D168	42.92314	36.77701	7.9	99.1	0.1	0.9
D169	43.59720	36.69328	0.8	100.0	0.0	0.0
D170	43.59564	36.68920	0.4	100.0	0.0	0.0
D171	42.65235	37.15690	6.7	95.2	0.3	4.8
D172	42.72842	37.15339	4.5	35.3	8.3	64.7
D173	42.74209	37.16246	21.7	47.7	23.8	52.3
D174	42.82838	37.20539	5.8	53.4	5.1	46.6
D175	42.67332	37.11089	1.3	100.0	0.0	0.0
D176	42.92061	36.84686	48.8	91.2	4.7	8.8
D177	42.92864	36.85628	35.7	92.6	2.9	7.4
D178	43.25033	36.67052	1.7	100.0	0.0	0.0
D179	43.25478	36.66924	0.7	100.0	0.0	0.0
D180	43.26181	36.66734	4.3	100.0	0.0	0.0
D181	43.27116	36.66503	1.9	100.0	0.0	0.0

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D182	43.27664	36.66386	0.8	100.0	0.0	0.0
D183	43.28240	36.66275	0.7	100.0	0.0	0.0
D184	43.29060	36.66119	2.4	100.0	0.0	0.0
D185	43.24961	36.67003	0.6	100.0	0.0	0.0
D186	43.25286	36.66912	0.7	100.0	0.0	0.0
D187	43.25748	36.66780	1.3	100.0	0.0	0.0
D188	43.26204	36.66644	1.1	100.0	0.0	0.0
D189	43.27845	36.66290	2.0	100.0	0.0	0.0
D190	43.29541	36.65963	1.7	100.0	0.0	0.0
D191	43.30530	36.65772	0.9	100.0	0.0	0.0
D192	43.31222	36.65647	0.3	100.0	0.0	0.0
D193	43.31700	36.65548	0.5	100.0	0.0	0.0
D194	43.24819	36.69129	1.1	100.0	0.0	0.0
D195	43.24523	36.72433	15.6	100.0	0.0	0.0
D196	43.24972	36.74544	0.5	100.0	0.0	0.0
D197	43.25038	36.74728	1.0	100.0	0.0	0.0
D198	43.58182	36.65525	0.4	100.0	0.0	0.0
D199	43.58128	36.65444	1.8	100.0	0.0	0.0
D200	43.58631	36.66022	0.7	100.0	0.0	0.0
D201	43.58955	36.66429	0.9	100.0	0.0	0.0
D202	43.59022	36.66972	0.3	100.0	0.0	0.0
D203	43.59181	36.67190	0.3	100.0	0.0	0.0
D204	43.59262	36.67276	0.3	100.0	0.0	0.0
D205	43.59251	36.67376	0.2	100.0	0.0	0.0
D206	43.59263	36.67573	0.3	100.0	0.0	0.0
D207	43.59332	36.67570	0.6	92.1	0.1	7.9
D208	43.59280	36.67741	0.2	100.0	0.0	0.0
D209	43.59214	36.67998	3.5	88.5	0.5	11.5
D210	43.59343	36.68168	0.5	100.0	0.0	0.0
D211	43.59337	36.68243	0.1	100.0	0.0	0.0
D212	43.59423	36.68467	0.2	100.0	0.0	0.0
D213	43.59415	36.68559	0.2	100.0	0.0	0.0
D214	43.59520	36.68765	0.4	100.0	0.0	0.0
D215	43.59493	36.68780	0.1	90.0	0.0	10.0
D216	43.59645	36.69013	0.7	100.0	0.0	0.0
D217	43.38768	36.94413	0.3	2.4	12.8	97.6
D218	43.39006	36.94745	5.3	22.6	18.3	77.4
D219	43.32243	37.05865	3.8	51.2	3.6	48.8
D220	43.40557	37.09361	0.4	12.2	3.0	87.8
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D222	43.41370	37.09023	0.5	13.3	3.1	86.7
D223	43.41290	37.08959	0.5	23.4	1.5	76.6
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D225	43.46428	37.09963	2.8	29.2	6.8	70.8
D226	43.07138	37.03942	20.6	83.5	4.1	16.5
D227	42.94026	36.83631	66.4	98.3	1.2	1.7
D228	43.18856	36.97347	7.2	12.9	48.6	87.1
			2329.8	**%49.9**	**2337.8**	**%50.1**

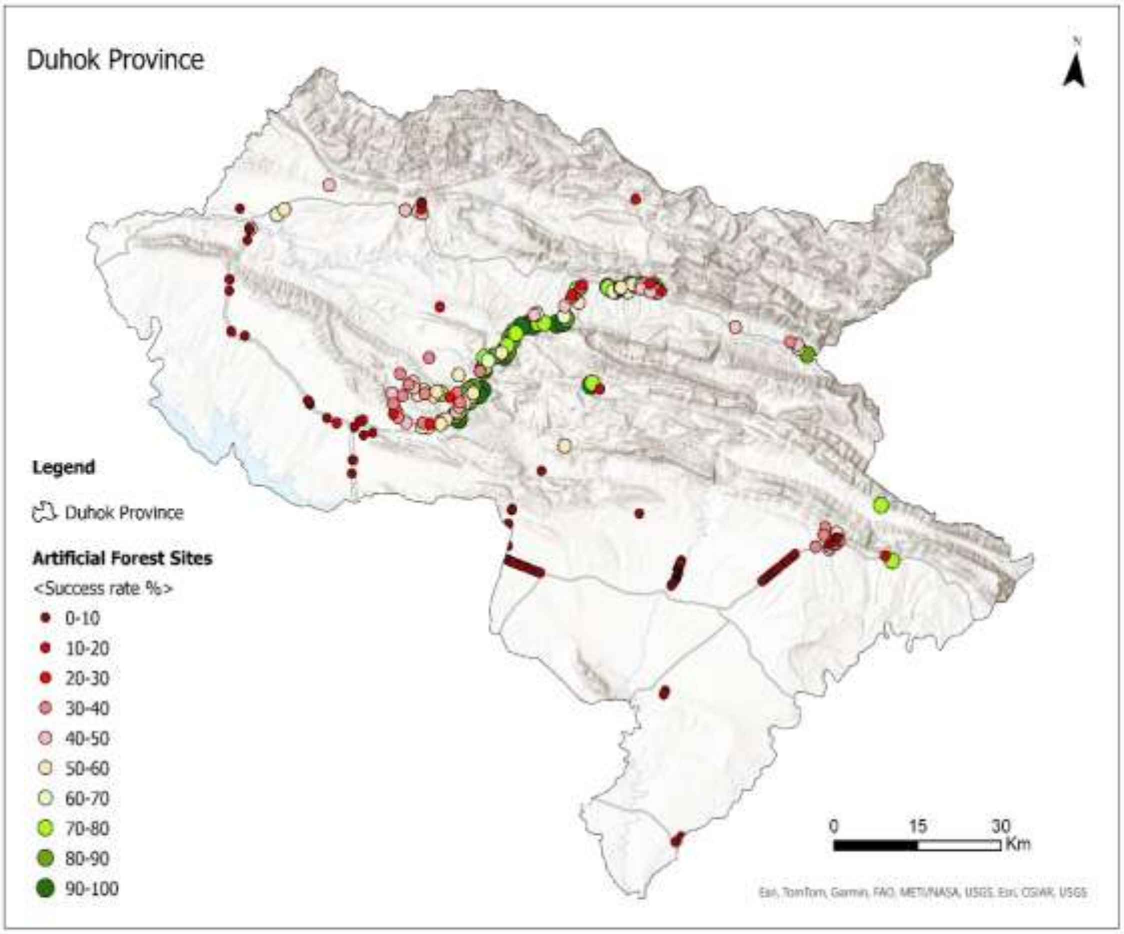

Figure 5. The spatial distribution of the Map of Success rate of artificial forest based on the total area afforested between 1973 and 2013 in Duhok Province.

The analysis of 229 artificial forest sites in Duhok Province, covering 4,667.6 ha, shows a nearly even split between forested (2,337.8 ha; 50.1%) and non-forested (2,329.8 ha; 49.9%) areas. This high proportion of surviving plantations, compared with other provinces in the Kurdistan Region, confirms Duhok's relatively strong performance in afforestation, consistent with its share of 37.3% of the region's total artificial forest area. Forest success rates vary greatly between sites. Many high-performing locations such as D065, D067, D070–D072, D077–D083, D087, D090–D094, D101, D103, D108,

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D217, and D228 achieved over 85% forest cover, with several exceeding 95%. These sites are likely situated in ecologically favorable zones with higher rainfall, suitable soils, and effective management. Conversely, a considerable number of sites, including D000–D007, D009–D011, D013, D138–D141, D144–D147, D175, and D178–D186, recorded 0–10% success rates, suggesting plantation failure or total loss due to factors such as unsuitable site selection, prolonged drought, overgrazing, or human disturbance.

The spatial distribution of success rates, as illustrated in Figure 5, reveals clear geographic patterns. High-success areas (green markers, 70–100%) are mainly concentrated in the central and southeastern mountainous zones, where topographic and climatic conditions favor forest establishment. In contrast, low-success areas (red markers, 0–30%) are prevalent in the southwestern and western lowland areas, indicating ecological constraints and possibly weaker management measures. The clustering of successful sites in higher elevation zones underscores the importance of microclimatic conditions and terrain in influencing afforestation outcomes. Duhok's overall 50.1% success rate is notably higher than that of Erbil (27.4%) and reflects the province's ecological advantages, historical investment in forestry, and possibly more robust protection regimes. However, the persistence of extensive low-success zones indicates that further improvements are possible. Recommended interventions include replanting in failed sites, implementing soil and water conservation techniques, enhancing seedling care in the first years, and strengthening protection against grazing and illegal logging.

3.3. Sulaymaniyah Province Case Study

The analysis of 172 artificial forest sites in Sulaymaniyah Province, covering a total of 4,223.7 ha, shows that 3,044.0 ha (72.1%) remains as non-forest, while only 1,179.8 ha (27.9%) is currently forested. This proportion indicates that Sulaymaniyah's forest survival rate is significantly lower than Duhok's 50.1% and close to Erbil's 27.4%, suggesting challenges in maintaining planted forest areas over the long term. The data reveal stark variability between sites. Several locations achieved high success rates, with forest cover exceeding 90%—including S024, S033, S035, S042, S045–S052, S053–S057, S065–S070, S076–S083, S085–S088, S097–S098, S101, S118, S121, S136–S137, S138, S140, S157–S159, and several sites in the southern districts. These sites likely benefited from favorable ecological conditions such as higher elevation, cooler microclimates, and better water availability, alongside effective management practices. Conversely, many locations exhibited very low forest cover (<10%), including S002, S036–S037, S042 (partial), S046–S050, S053–S057, S118, S138, and others in drier or heavily grazed zones. These areas may have suffered from plantation failure due to poor site selection, inadequate post-planting care, or exposure to prolonged drought periods. Spatially, high-success areas appear scattered across the province but tend to cluster in specific upland regions, especially in areas with

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favorable climatic and soil conditions. In contrast, low-success areas are more widely distributed, often occurring in zones affected by intensive agriculture, overgrazing, or human settlement expansion. The wide distribution of failure zones indicates that ecological limitations are compounded by anthropogenic pressures. Overall, Sulaymaniyah's artificial forest survival rate of 27.9% highlights the need for targeted intervention. Efforts should focus on replanting failed sites with more drought-resistant species, improving soil moisture retention through mulching and contour planting, and enhancing protection against grazing. Lessons from successful zones such as the importance of microclimate, soil quality, and consistent maintenance should be applied strategically across low-performing areas to improve the province's long-term forest cover.

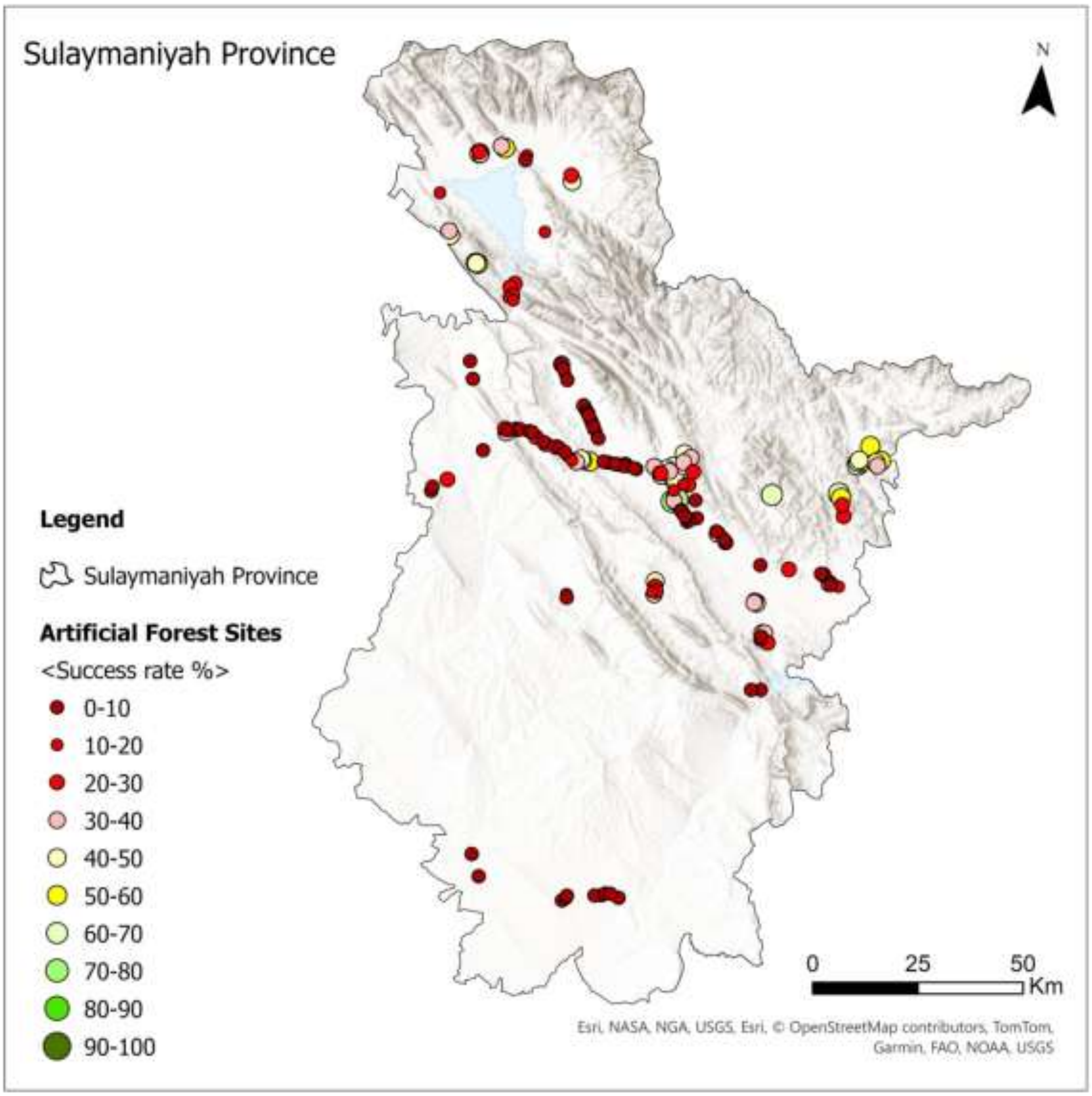

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Figure 6. The spatial distribution of the Map of Success rate of artificial forest based on the total area afforested between 1973 and 2013 in Sulaymaniyah Province.

Table 4. Percentage of successful artificial forests based on the total area afforested between 1973 and 2013 in Sulaymaniyah province

Sulaymaniyah Locations	X	Y	Non-Forest Area (ha)	%	Forest Area (ha)	%
S000	45.856975	35.360381	7.7	94.0	0.5	6.0
S001	45.852816	35.359635	3.9	61.4	2.5	38.6
S002	45.856438	35.356739	2.8	100.0	0.0	0.0
S003	45.870503	35.544175	9.7	48.9	10.1	51.1
S004	45.863445	35.553119	12.1	35.5	22.0	64.5
S005	45.169162	35.300522	9.5	82.9	2.0	17.1
S006	45.170561	35.293260	34.5	95.5	1.6	4.5
S007	45.914970	35.622482	25.9	48.1	28.0	51.9
S008	45.911575	35.627784	17.9	59.0	12.4	41.0
S009	45.907653	35.622479	12.3	50.6	12.0	49.4
S010	45.908183	35.616902	6.9	31.5	15.1	68.5
S011	44.871459	35.995047	0.3	47.6	0.3	52.4
S012	44.872901	35.994116	1.3	59.8	0.8	40.2
S013	44.877177	35.993181	10.7	47.1	12.0	52.9
S014	44.860790	36.229461	1.5	42.9	2.0	57.1
S015	44.859755	36.232463	5.2	75.2	1.7	24.8
S016	45.691956	35.245275	3.0	69.7	1.3	30.3
S017	45.687547	35.243869	5.7	50.7	5.6	49.3
S018	45.661461	35.311782	0.6	61.2	0.4	38.8
S019	45.660225	35.308861	2.1	66.6	1.0	33.4
S020	45.666019	35.308512	31.3	52.9	27.9	47.1
S021	45.128195	35.610748	2.7	86.1	0.4	13.9
S022	45.123394	35.612546	2.7	91.6	0.3	8.4
S023	45.115514	35.613753	1.3	79.1	0.3	20.9
S024	45.049763	35.642266	2.8	97.9	0.1	2.1
S025	45.135023	35.605124	0.9	88.5	0.1	11.5
S026	45.042203	35.643307	2.8	91.0	0.3	9.0
S027	45.018210	35.645688	5.0	90.8	0.5	9.2
S028	45.159057	35.587093	2.1	86.7	0.3	13.3
S029	45.147731	35.596318	5.2	82.4	1.1	17.6
S030	45.003961	35.646563	8.3	80.9	2.0	19.1
S031	45.087463	35.618371	1.4	78.4	0.4	21.6
S032	45.081133	35.622567	3.6	97.6	0.1	2.4
S033	45.114165	35.791240	0.8	96.4	0.0	3.6
S034	45.116219	35.791263	3.1	68.5	1.4	31.5
S035	45.202454	35.674424	5.0	95.2	0.3	4.8

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S036	45.207227	35.666670	0.8	100.0	0.0	0.0
S037	45.209809	35.662370	1.2	100.0	0.0	0.0
S038	45.212741	35.657563	1.1	94.8	0.1	5.2
S039	45.217907	35.650818	0.4	82.2	0.1	17.8
S040	45.223877	35.639178	1.7	96.5	0.1	3.5
S041	45.225358	35.638268	0.8	97.6	0.0	2.4
S042	45.121238	35.781336	1.8	100.0	0.0	0.0
S043	45.121173	35.778880	1.8	81.8	0.4	18.2
S044	45.125273	35.771417	1.1	86.3	0.2	13.7
S045	45.133274	35.758135	0.7	100.0	0.0	0.0
S046	45.179722	35.705696	1.3	100.0	0.0	0.0
S047	45.181922	35.703268	0.4	100.0	0.0	0.0
S048	45.183179	35.703719	0.6	100.0	0.0	0.0
S049	45.180616	35.706572	1.5	100.0	0.0	0.0
S050	45.190114	35.694229	2.1	100.0	0.0	0.0
S051	45.194438	35.689415	0.7	100.0	0.0	0.0
S052	45.195753	35.685419	0.5	100.0	0.0	0.0
S053	45.458298	35.492268	0.4	100.0	0.0	0.0
S054	45.454508	35.496302	5.1	100.0	0.0	0.0
S055	45.460130	35.490557	0.2	100.0	0.0	0.0
S056	45.569342	35.440716	0.6	100.0	0.0	0.0
S057	45.571046	35.439245	0.1	100.0	0.0	0.0
S058	45.570986	35.442246	2.5	88.8	0.3	11.2
S059	45.549509	35.456236	0.8	100.0	0.0	0.0
S060	45.553065	35.450236	29.4	61.8	18.2	38.2
S061	45.477022	35.475661	0.8	100.0	0.0	0.0
S062	45.575765	35.433489	0.4	78.8	0.1	21.2
S063	45.462625	35.487940	0.2	100.0	0.0	0.0
S064	45.459520	35.489650	1.6	100.0	0.0	0.0
S065	45.576603	35.434377	0.7	98.7	0.0	1.3
S066	45.468778	35.481596	1.0	100.0	0.0	0.0
S067	45.453481	35.495845	1.0	100.0	0.0	0.0
S068	45.455649	35.493476	1.8	100.0	0.0	0.0
S069	45.464656	35.484018	0.6	100.0	0.0	0.0
S070	45.471498	35.473095	34.4	92.4	2.9	7.6
S071	45.456155	35.591810	115.8	58.3	82.7	41.7
S072	45.452533	35.599045	14.6	68.6	6.7	31.4
S073	45.462602	35.602280	20.6	58.9	14.4	41.1
S074	45.478913	35.580106	267.9	76.7	81.5	23.3
S075	45.470559	35.610250	179.2	60.5	116.9	39.5
S076	45.254445	35.587729	2.9	98.7	0.0	1.3
S077	45.329265	35.578290	0.8	92.6	0.1	7.4
S078	45.324957	35.579203	0.7	100.0	0.0	0.0
S079	45.283056	35.584546	6.7	94.5	0.4	5.5

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S080	45.284362	35.585168	4.2	96.8	0.1	3.2
S081	45.292842	35.584182	1.1	98.3	0.0	1.7
S082	45.295567	35.583112	2.9	98.7	0.0	1.3
S083	45.302916	35.582983	0.8	97.5	0.0	2.5
S084	45.299977	35.585954	20.9	75.0	7.0	25.0
S085	45.246946	35.588382	0.9	100.0	0.0	0.0
S086	45.242578	35.589047	2.0	100.0	0.0	0.0
S087	45.273308	35.586366	1.3	100.0	0.0	0.0
S088	45.273311	35.585659	1.4	95.1	0.1	4.9
S089	44.978236	35.645004	58.7	73.7	20.9	26.3
S090	44.984409	35.642393	4.5	100.0	0.0	0.0
S091	44.981846	35.636705	32.8	66.8	16.3	33.2
S092	45.183185	35.591408	7.1	53.9	6.0	46.1
S093	45.187853	35.588859	3.1	51.7	2.9	48.3
S094	45.205276	35.587301	57.4	41.0	82.5	59.0
S095	45.171481	35.584547	4.3	65.0	2.3	35.0
S096	45.008107	35.645165	9.4	73.9	3.3	26.1
S097	45.139763	35.604075	51.0	97.7	1.2	2.3
S098	45.496166	35.481739	37.4	99.5	0.2	0.5
S099	45.375889	35.586258	10.7	66.4	5.4	33.6
S100	45.452411	35.617383	23.1	50.0	23.1	50.0
S101	45.489829	35.519558	85.2	97.2	2.5	2.8
S102	44.986577	36.231734	25.4	82.7	5.3	17.3
S103	44.863683	36.226976	6.2	63.8	3.5	36.2
S104	44.916656	36.247871	8.0	65.1	4.3	34.9
S105	44.926915	36.244247	63.2	44.1	80.1	55.9
S106	44.978514	35.956640	92.0	73.5	33.2	26.5
S107	44.964324	35.926420	3.2	82.9	0.7	17.1
S108	45.047538	36.071080	7.5	83.1	1.5	16.9
S109	44.799372	36.049405	4.6	55.0	3.7	45.0
S110	45.688662	35.541214	6.4	39.4	9.8	60.6
S111	45.836535	35.377554	19.0	75.6	6.1	24.4
S112	45.830109	35.379753	7.9	90.8	0.8	9.2
S113	45.842580	35.372269	17.1	81.2	4.0	18.8
S114	45.874865	35.529297	1.7	77.2	0.5	22.8
S115	45.877883	35.353957	13.2	87.5	1.9	12.5
S116	45.938551	35.658341	7.4	41.5	10.4	58.5
S117	44.874862	35.784287	4.6	100.0	0.0	0.0
S118	44.797145	35.500982	145.5	100.0	0.0	0.0
S119	44.925118	35.595609	23.0	91.5	2.1	8.5
S120	44.763827	36.138752	11.0	84.6	2.0	15.4
S121	44.982925	36.221812	49.5	90.6	5.1	9.4
S122	45.392880	35.317569	15.9	80.0	4.0	20.0
S123	45.399405	35.330047	62.4	70.9	25.6	29.1

S124	45.401986	35.319885	21.5	74.2	7.5	25.8
S125	45.397497	35.312775	6.2	66.9	3.0	33.1
S126	45.398325	35.340556	52.1	54.9	42.8	45.1
S127	45.110319	36.183222	21.9	57.8	16.0	42.2
S128	45.106590	36.195925	269.6	75.8	85.9	24.2
S129	45.880227	35.505158	34.1	73.2	12.5	26.8
S130	44.795299	36.059240	15.9	69.1	7.1	30.9
S131	45.745238	35.384520	31.3	74.8	10.6	25.2
S132	44.976413	35.920606	37.6	89.1	4.6	10.9
S133	44.974079	35.930951	8.2	78.5	2.3	21.5
S134	44.966347	35.947584	70.1	74.4	24.1	25.6
S135	45.702146	35.225031	15.5	79.3	4.0	20.7
S136	45.691929	35.123505	32.3	97.2	0.9	2.8
S137	45.670137	35.389638	35.7	92.2	3.0	7.8
S138	44.800157	35.510556	78.6	100.0	0.0	0.0
S139	45.061172	35.631601	36.1	75.1	12.0	24.9
S140	44.885519	35.746399	24.4	93.3	1.7	6.7
S141	45.431113	35.564807	33.4	57.3	24.9	42.7
S142	45.418037	35.571457	16.2	51.7	15.1	48.3
S143	45.434730	35.557159	2.0	44.3	2.5	55.7
S144	45.428379	35.586901	0.7	38.2	1.1	61.8
S145	45.392598	35.572429	2.9	70.2	1.2	29.8
S146	45.430896	35.537877	8.7	83.2	1.8	16.8
S147	45.433403	35.516218	1.2	64.4	0.6	35.6
S148	45.429689	35.514411	0.8	27.3	2.2	72.7
S149	45.441176	35.518418	1.0	27.9	2.6	72.1
S150	45.469066	35.551942	11.9	70.5	5.0	29.5
S151	45.455307	35.551513	6.2	84.8	1.1	15.2
S152	45.407809	35.582188	0.5	53.5	0.5	46.5
S153	45.416701	35.578050	0.4	68.8	0.2	31.3
S154	45.399337	35.571087	0.5	35.5	0.9	64.5
S155	45.394628	35.571508	1.1	75.5	0.3	24.5
S156	44.837380	35.527804	1.5	74.3	0.5	25.7
S157	45.666314	35.122081	5.1	97.3	0.1	2.7
S158	45.682327	35.230601	19.9	93.1	1.5	6.9
S159	45.684195	35.237402	11.1	93.3	0.8	6.7
S160	45.955504	35.624610	4.0	51.4	3.8	48.6
S161	45.960288	35.617922	1.6	68.2	0.8	31.8
S162	45.968333	35.628734	3.2	42.8	4.2	57.2
S163	44.969990	34.731601	5.7	100.0	0.0	0.0
S164	44.991540	34.685270	11.9	100.0	0.0	0.0
S165	45.357857	34.659491	87.0	99.9	0.1	0.1
S166	45.212039	34.645854	13.2	100.0	0.0	0.0
S167	45.312927	34.662751	6.4	100.0	0.0	0.0

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S168	45.294922	34.661215	6.4	100.0	0.0	0.0
S169	45.323532	34.667221	3.0	100.0	0.0	0.0
S170	45.336153	34.666901	7.7	100.0	0.0	0.0
S171	45.220725	34.652129	0.9	100.0	0.0	0.0
S172	45.223749	34.656431	1.0	100.0	0.0	0.0
			3044.0	**%72.1**	**1179.8**	**%27.9**

3.4. Halabja Province Case Study

The assessment of 15 artificial forest sites in Halabja Province, covering a total of 636.3 ha**,** reveals that 342.5 ha (53.8%) are non-forest, while 293.8 ha (46.2%) remain forested. This gives Halabja the second-highest artificial forest survival rate among the provinces in the Kurdistan Region, following Duhok (50.1%), and significantly higher than Erbil (27.4%) and Sulaymaniyah (27.9%).

The site-level data reveal a relatively balanced distribution between successful and unsuccessful plantations. Several locations, such as H005, H007–H008, H010–H011, and H014, achieved forest cover rates above 60%, with H014 recording the highest success rate at 63.3%**. T**hese sites are likely benefiting from favorable ecological conditions, including suitable elevation, adequate soil moisture, and reduced human or grazing pressures. In contrast, other sites, including H003, H006, and H001, displayed relatively low forest cover (<20%), suggesting plantation failure or significant degradation, possibly due to overgrazing, insufficient post-planting care, or unsuitable site selection. The spatial distribution shown in Figure (Halabja Province) highlights a clear clustering of high-success sites (green markers, 60–90%) in the southeastern and central parts of the province. Lower success rates (red markers, 0–30%) are concentrated in certain northern and central locations, indicating localized ecological or anthropogenic constraints. The terrain and climate patterns of Halabja, with its mixture of mountainous and valley environments, appear to play a significant role in influencing plantation outcomes.

Halabja's relatively high overall forest success rate (46.2%) suggests that its afforestation strategies have been moderately effective, especially when compared to Erbil and Sulaymaniyah. Nevertheless, the persistence of nearly half the surveyed area as non-forest underscores the need for targeted interventions in low-performing sites. Recommended actions include soil and water conservation measures, introduction of more drought-tolerant tree species, and reinforcement of grazing controls to ensure seedling survival.

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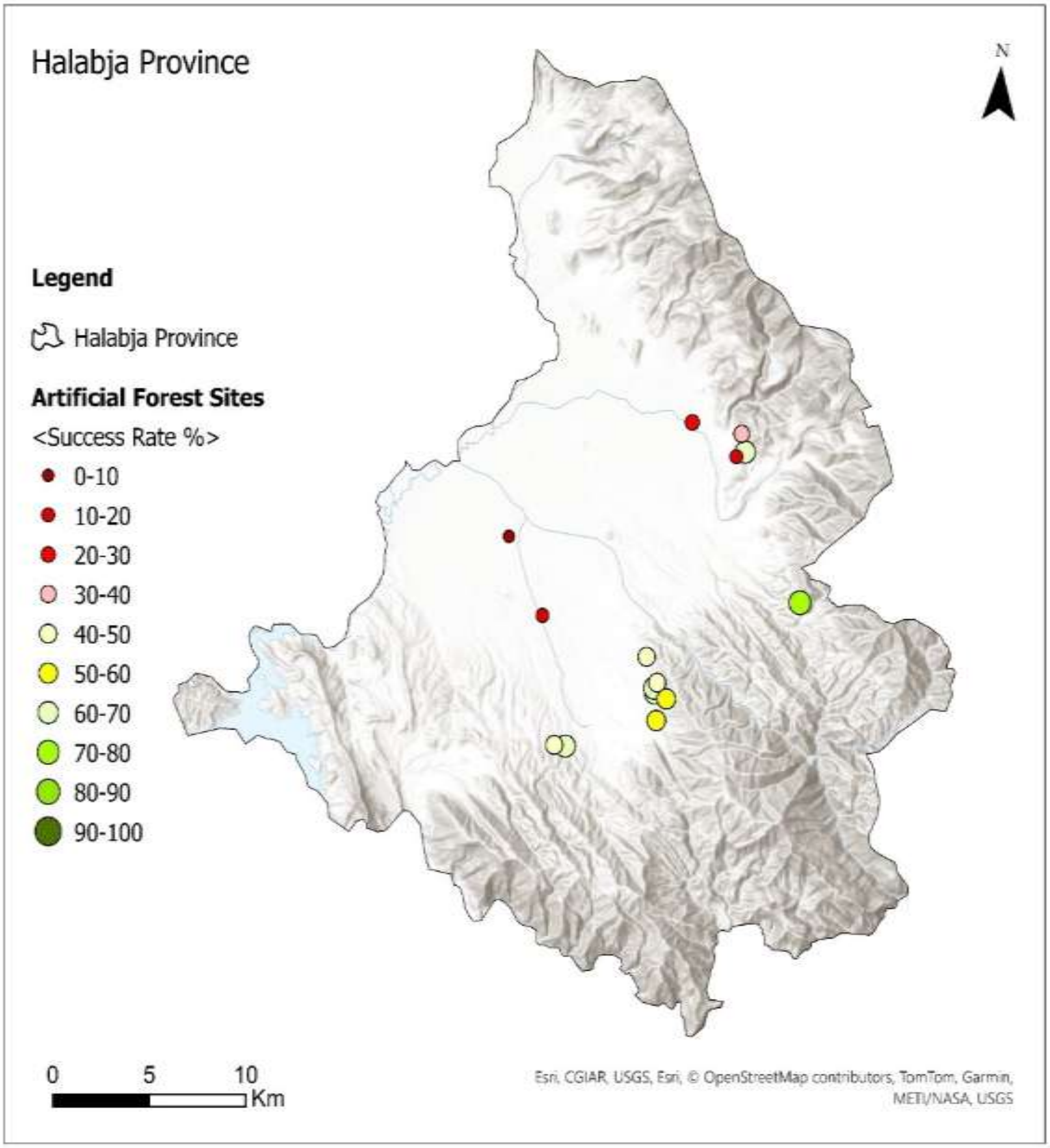

Figure 7. The spatial distribution of the Map of Success rate of artificial forest based on the total area afforested between 1973 and 2013 in Halabja Province.

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Table 5. Percentage of successful artificial forests based on the total area afforested between 1973 and 2013 in Sulaymaniyah province

Halabja Locations	X	Y	Non-Forest		Forest	
			Area (ha)	%	Area (ha)	%
H000	45.96181	35.21469	30.1	85.0	5.3	15.0
H001	46.02226	35.19992	45.82	59.9	30.7	40.1
H002	46.02973	35.17305	23.49	43.9	30	56.1
H003	45.94033	35.24747	35.26	99.0	0.36	1.0
H004	46.04104	35.30114	17.22	72.8	6.44	27.2
H005	46.07203	35.28993	1.34	34.5	2.54	65.5
H006	46.06717	35.28778	3.34	85.9	0.55	14.1
H007	46.02733	35.18675	1.1	37.2	1.86	62.8
H008	46.02783	35.18472	1.48	36.7	2.55	63.3
H009	46.02901	35.18924	6.91	56.0	5.42	44.0
H010	46.03474	35.18256	40.82	49.4	41.81	50.6
H011	46.10762	35.22719	1.56	26.7	4.28	73.3
H012	46.06949	35.29767	26.05	66.1	13.37	33.9
H013	45.97258	35.15978	37.97	57.8	27.77	42.2
H014	45.97888	35.15956	70.04	36.7	120.87	63.3
			342.5	**%53.8**	**293.8**	**%46.2**

3.5. Total biomass production

Table 6 provides the updated estimates of Total Biomass Production (TBP), carbon stored in dry matter, and CO_2 equivalent for the forested areas within the four provinces of the Kurdistan Region (KRI): Erbil, Duhok, Sulaymaniyah, and Halabja. The calculations use the WaPOR V3 TBP raster (kg/ha/year) masked to include forest pixels only (mask value = 2). Each raster pixel is 100 m × 100 m = 1 hectare.

3.6. Assessment of Aboveground Biomass and CO_2 Storage in Forest Ecosystems

Table 6 presents detailed data on biomass and carbon stock collected from 13 sample plots across the study area, covering Erbil, Duhok, and Sulaymaniyah. The variables include the number of trees per plot, tree diameter (Dq), total fresh and dry weight per tree and plot, and estimated carbon content at the tree, plot, and hectare levels. The data reveal significant variability in biomass and carbon stocks among plots, reflecting differences in stand structure, tree density, and possibly species composition. Notably, plots 9 and 13 exhibited the highest biomass and carbon values, with dry weight per hectare reaching 26,687.9 kg/ha and 39,692.1 kg/ha, respectively, and corresponding carbon stocks per hectare exceeding 90,000 kg and 238,000 kg.

These high values suggest the presence of larger or denser trees, possibly due to site conditions or management history. In contrast, plots like 1 and 3 had considerably lower biomass and carbon levels, indicating younger or less dense stands.

plots was estimated at 501,187.0 kg·ha⁻¹. The coordinates indicate that sampling covered a broad geographic range, with latitudes from 35.33° N to 37.02° N and longitudes from 44.23° E to 43.11° E. This distribution spans lowland to highland zones, encompassing diverse site conditions and the environmental gradients.

Table 6. Total biomass production and carbon/CO_2 equivalents by province in the Kurdistan Region of Iraq.

Province	Area (ha)	SUM (kg DM)	Mean (kg/ha)	Carbon (kg C)	CO2 (kg)	CO2 (Mega tones)
Erbil	328,669	3,395,477,409	10,330.99	1,527,964,834	5,607,630,941	5.608
Duhok	403,762	4,673,306,720	11,574.41	2,102,988,024	7,717,966,048	7.718
Sulaymaniyah	309,672	2,835,169,730	9,155.40	1,275,826,378	4,682,282,809	4.682
Halabja	17,659	154,869,527	8,770.01	69,691,287	255,767,024	0.256
Total	**1,059,762**	**11,058,823,386**	**—**	**4,976,470,524**	**18,263,646,822**	**18.264**

The measurements in Table 6 clearly show variation in tree biomass and carbon stock across the 13 sampled plots. The total fresh weight (TFW) per tree ranged from as low as 3.6 kg in plot 3 to as high as 476.6 kg in plot 13, while the total dry weight (TDW) per tree ranged from 8.0 kg to 330.8 kg. At the plot level, TFW ranged from 55.9 kg in plot 1 to 5,719.6 kg in plot 13, and TDW from 48.1 kg to 3,969.2 kg. When extrapolated to a hectare basis, TDW ranged between 480.9 kg·ha⁻¹ and 39,692.1 kg·ha⁻¹, with a total TDW across all plots amounting to 105,678.4 kg·ha⁻¹. Carbon storage varied widely among plots as well. The carbon content per tree ranged from 24.0 kg in plot 1 to 1,984.6 kg in plot 13. At the plot level, this translated to 144.3 kg to 23,815.23 kg, and on a per-hectare basis, from 1,442.8 kg·ha⁻¹ to 238,152.3 kg·ha⁻¹. Overall, the total carbon stock for all

The results highlight significant variation in biomass production and carbon storage capacity between plots, which appears closely linked to differences in tree diameter at breast height (DBH), stand density, and site conditions. Plot 13 recorded the highest biomass and carbon values, likely due to its combination of large tree diameters (35.4 cm DBH), a relatively high number of trees, and favorable environmental or soil conditions. In contrast, plots 1 and 3 showed the lowest values, suggesting younger stands, lower productivity, or suboptimal growth conditions. The data confirm the strong relationship between DBH and biomass accumulation, as plots with larger DBH consistently showed higher TFW, TDW, and carbon storage. This supports the established use of DBH as a reliable

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predictor of forest carbon stock in biomass estimation models. When scaled to a hectare, high-performing plots such as 9, 11, and particularly 13 contributed disproportionately to the total carbon stock, indicating that targeted silvicultural interventions in lower-yielding plots could enhance overall sequestration potential.

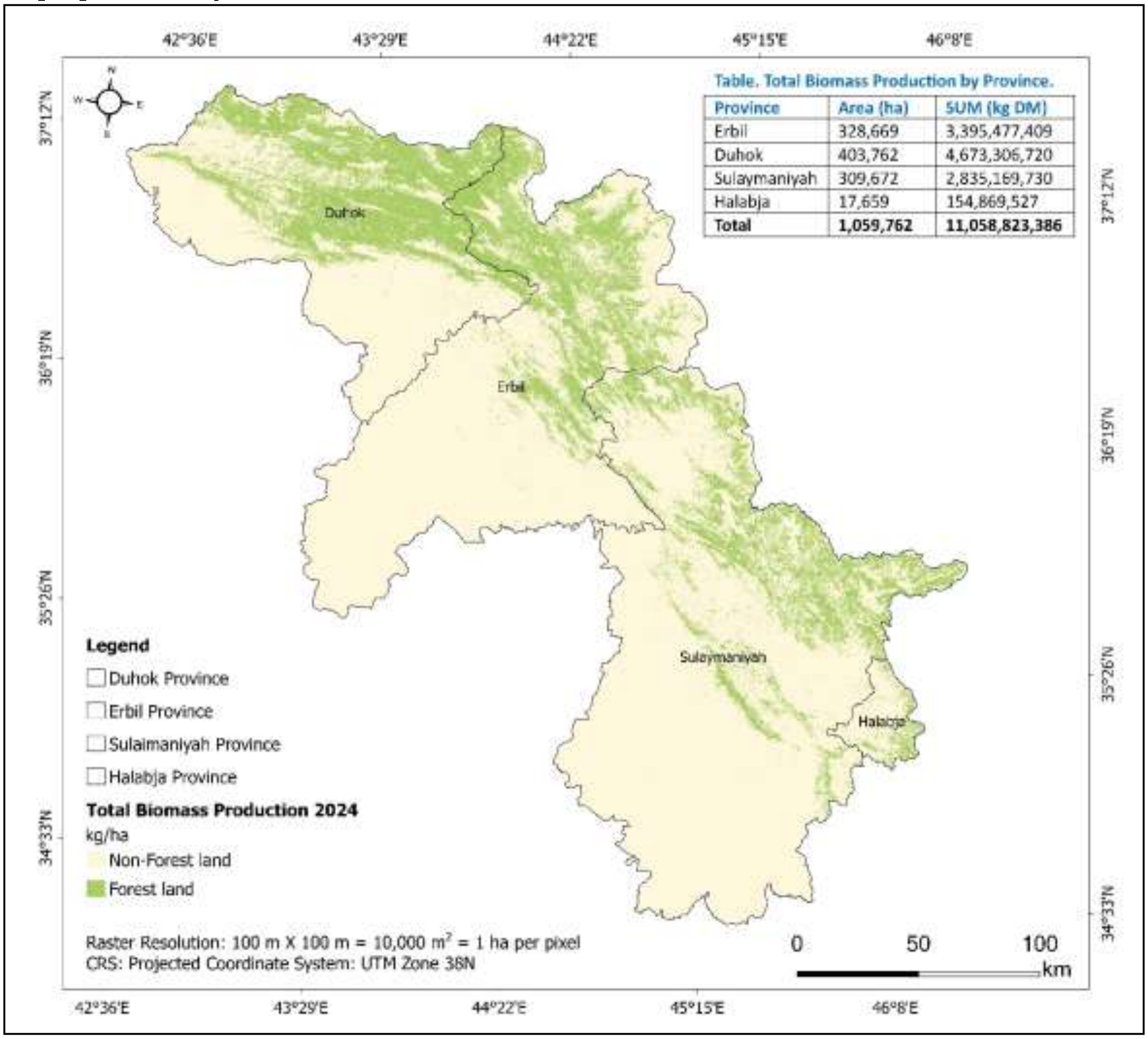

Figure 8. Spatial distribution of above-ground biomass (kg ha^{-1}) in the Kurdistan Region of Iraq (KRI) for 2024, derived from FAO-WaPOR v3 (100 m). Provincial totals of forest area and total biomass (kg dry matter) are reported in the inset table.

From a carbon sequestration perspective, the combined carbon stock of over 500 $t \cdot ha^{-1}$ demonstrates the significant role of these forested areas as carbon sinks. Managing high-productivity plots for sustained growth and expanding them could contribute meaningfully to climate change mitigation goals. The variation observed between plots is also likely influenced by geographic and ecological factors such as altitude, soil fertility, and rainfall, which warrants further investigation.

4. Discussion

The analysis of artificial forest plantations across the Kurdistan Region between 1973 and 2013 reveals substantial spatial and temporal variability in plantation survival rates, strongly influenced by ecological suitability, site management, and anthropogenic pressures. Of the four provinces assessed, Duhok recorded the highest overall forest survival rate (50.1%), followed closely by Halabja (46.2%), while Erbil (27.4%) and Sulaymaniyah (27.9%) exhibited considerably lower success rates. The superior performance in Duhok can be attributed to its predominantly mountainous terrain, favorable microclimates, and historical investment in forestry programs. Many high-success sites in Duhok are located in elevated areas with higher rainfall, reduced temperature extremes, and lower levels of grazing pressure. Similar patterns are evident in Halabja, where successful plantations cluster in the southeastern uplands and central valleys, benefitting from a combination of suitable soils and microclimatic conditions. In contrast, the low survival rates in Erbil and Sulaymaniyah reflect a combination of environmental and management challenges. Large portions of their artificial forest areas are located in semi-arid lowlands, where high summer temperatures, limited precipitation, and poor soil moisture retention reduce seedling survival. Furthermore, extensive agricultural expansion, urbanization, and uncontrolled grazing have contributed to plantation degradation. The prevalence of low-success sites (<30% forest cover) in these provinces underscores the vulnerability of afforestation projects when ecological suitability and management are not adequately matched. Across the region, high-survival plantations tend to form clusters, suggesting that localized conditions such as slope orientation, elevation, and soil depth play a decisive role in determining plantation outcomes. Conversely, low-survival areas are more widely distributed and often coincide with zones of high human activity. This spatial pattern highlights the importance of integrating ecological assessment into afforestation planning.

The findings also emphasize the role of post-planting management in ensuring long-term success. In sites where initial planting efforts were followed by irrigation, soil conservation, and protection from grazing, survival rates were consistently higher. Conversely, sites with minimal follow-up care experienced high mortality rates, even when initial site conditions were favorable. From a policy perspective, the results call for a shift from uniform afforestation programs to targeted, site-specific approaches. Provinces with low success rates should prioritize reforestation in ecologically suitable zones and adopt adaptive management strategies, including the use of drought-tolerant species, water harvesting techniques, and community-based protection measures. Meanwhile, high-performing provinces should consolidate gains by protecting existing forests from degradation and using them as reference models for other regions. By combining GIS-based spatial analysis with on-the-ground assessment, this study provides a clear framework for prioritizing reforestation efforts in the Kurdistan Region. Such an approach not only maximizes the return on investment in afforestation programs but also strengthens the ecological resilience of the region’s forest

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landscapes in the face of climate change and increasing land-use pressures.

5. Conclusion

The evaluation of artificial forest plantations across the Kurdistan Region demonstrates marked differences in afforestation success among provinces, shaped by a combination of ecological and anthropogenic factors. Duhok's relatively high forest survival rate (50.1%) reflects the advantage of suitable topography, climatic conditions, and more effective forest protection measures, while Halabja's performance (46.2%) indicates moderate success with potential for further improvement. In contrast, the low survival rates in Erbil (27.4%) and Sulaymaniyah (27.9%) point to persistent challenges, including poor site selection, insufficient maintenance, and vulnerability to grazing and land-use change. Spatial analysis confirms that high-success plantations are concentrated in upland and mountainous areas, suggesting that afforestation efforts are more likely to succeed under favorable microclimatic conditions and on well-selected sites. Conversely, low-success zones require targeted interventions such as replanting with drought-tolerant species, implementing soil and water conservation measures, and strengthening grazing control policies. This study demonstrates the substantial carbon storage capacity of the Kurdistan Region's forests, with total annual biomass production estimated at over 11 billion kg dry matter and carbon sequestration exceeding 18 million tonnes of CO_2 . Field plot assessments confirmed large variability across sites, with biomass and carbon stocks strongly influenced by tree diameter, stand density, and site conditions. High-yield plots, particularly in Duhok and Erbil, significantly enhanced overall sequestration, whereas younger or sparsely stocked plots in Sulaymaniyah and Halabja showed comparatively lower contributions.

The results emphasize the importance of incorporating site-specific forest management and silvicultural interventions to improve productivity in underperforming plots, thereby maximizing the carbon sequestration potential of the region's forests. Expanding forest cover in high-potential zones and maintaining existing stands could play a critical role in Iraq's climate mitigation strategies. Moreover, the study provides a scientific baseline for policymakers and forest managers to design strategies that enhance both ecosystem services and resilience against climate change.

For sustainable forest expansion in the Kurdistan Region, afforestation programs must adopt a site-specific approach, integrating ecological suitability with robust management and protection strategies. The use of GIS-based spatial prioritization, informed by survival rate mapping, can optimize resource allocation and enhance the resilience of forest ecosystems, contributing to biodiversity conservation, soil stability, and climate change mitigation in the region.

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