



Tree oxygen release dynamics in Uzbekistan: GIS and remote-sensing evidence from phenology, biomass development, spectral response, and climate scenarios

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ABSTRACT

Tree oxygen release is not a fixed ecological value, because it changes with phenological phase, biomass development, canopy condition, and long-term climate stress. This study assesses the dynamic controls on tree oxygen release in Uzbekistan using GIS and remote-sensing-supported evidence derived from phenological, biomass, spectral, correlation, and climate-scenario materials. The analysis used species-level values for oak, pine, birch, and plane tree across four phenological phases and four biomass-development stages, together with landscape-specific graphical evidence for saxaul, tamarix, juniper, birch, maple, oak, pine, and almond. The phenological results showed that oxygen release increased sharply from early development to middle development, with the mean value rising from 135 to 287.5 kg ha⁻¹ yr⁻¹, before declining to 270 kg ha⁻¹ yr⁻¹ during reproduction and 48.75 kg ha⁻¹ yr⁻¹ during dormancy. The biomass results showed an even stronger pattern: mean oxygen release increased from 98.75 kg ha⁻¹ yr⁻¹ at the initial biomass stage to 337.5 kg ha⁻¹ yr⁻¹ at mature biomass, then declined to 175 kg ha⁻¹ yr⁻¹ during aging. Spectral-signature and correlation materials confirmed that oxygen release is linked to vegetation vigor indicators such as NDVI and LAI, although the available correlation values remain exploratory. Scenario projections suggested increasing oxygen-release potential under RCP 4.5 and declining performance under RCP 8.5. The study shows that oxygen-release assessment can support restoration monitoring in Uzbekistan when it is interpreted as an ecological productivity indicator and integrated with GIS, remote sensing, and long-term climate adaptation planning.

Keywords:

Oxygen release, phenology, biomass, NDVI, LAI, GIS, remote sensing, RCP 4.5, RCP 8.5, Uzbekistan

1. Introduction

Tree oxygen release is closely connected with photosynthesis, canopy activity, leaf area, biomass accumulation, and environmental conditions. For this reason, it should not be presented as a constant value attached only to tree species. A young tree, a mature tree, and a dormant tree do not have the same oxygen-release potential. Similarly, a tree growing under favourable moisture and canopy conditions cannot be compared directly with a tree under heat stress, salinity, drought, or senescence. In ecological assessment, oxygen release is therefore more useful when it is treated as an indicator of vegetation productivity and physiological activity rather than as an isolated ecosystem service (Bonan, 2008; Nowak et al., 2007).

Phenology is one of the most important controls on this process. During early growth, leaf area and photosynthetic capacity are still developing. During the middle growth phase, canopy activity is usually strongest, which supports higher oxygen release. During reproduction, part of the plant's physiological energy is redirected to reproductive processes, and during dormancy, photosynthetic activity decreases sharply. These seasonal differences are widely recognized in vegetation phenology studies, where the timing of green-up, peak growth, senescence, and dormancy is used to understand ecosystem functioning and climate response (Cleland et al., 2007; Richardson et al., 2013; Zeng et al., 2020).

Biomass development is another major factor. Oxygen release increases as trees accumulate woody and foliar biomass, expand the crown, and improve canopy closure. However, the highest values are usually expected at mature biomass stages rather than at the initial planting stage. In aging stands, oxygen release may decline because of reduced physiological activity, canopy thinning, branch mortality, or lower productivity. This means that restoration projects should not be assessed only through planted area or seedling numbers. Long-term stand development, survival, crown expansion, and biomass maturity are more relevant

indicators of real ecological performance (Asner et al., 2010; Khamzina et al., 2006, 2008).

Remote sensing and GIS provide the spatial basis for monitoring these patterns. NDVI, EVI, LAI, canopy density, and spectral reflectance can help evaluate vegetation vigor and spatial differences in ecosystem condition. NDVI is particularly useful for assessing greenness and vegetation response to environmental change, while EVI improves sensitivity in areas with dense canopy or atmospheric influence. These indicators cannot measure oxygen release directly, but they can support oxygen-release modelling by showing where vegetation is active, dense, and structurally developed (Gorelick et al., 2017; Huete et al., 2002; Pettorelli et al., 2005; Tucker, 1979).

Uzbekistan provides a relevant case for such an assessment because its ecosystems include deserts, rangelands, foothills, mountains, irrigated oases, urban green spaces, and degraded territories affected by drought and land degradation. The Aral Sea crisis and wider dryland degradation problems make vegetation restoration especially important. In this context, oxygen release should be understood together with other ecological benefits, including carbon sequestration, land stabilization, dust reduction, microclimate regulation, and improvement of habitat conditions (Kariyeva & van Leeuwen, 2011; Micklin, 2016).

The objective of this article is to assess how tree oxygen release in Uzbekistan changes across phenological phases, biomass-development stages, spectral vegetation response, and long-term climate scenarios. The article is not framed as a single field experiment. Instead, it is a structured synthesis of dissertation-derived tables and figures, supported by ecological interpretation and literature-based discussion. The study addresses four questions: how oxygen release changes across phenological phases, how biomass stage influences oxygen-release potential, how spectral and vegetation-index indicators support spatial interpretation, and how RCP 4.5 and RCP 8.5 scenarios affect long-term oxygen-release trajectories.

2. Materials and Methods

The study used tables and figures derived from the dissertation dataset on GIS-based assessment of oxygen release from trees in Uzbekistan. The quantitative backbone of the article consists of two tables. The first table reports oxygen-release values for oak, pine, birch, and plane tree across four phenological phases: early development, middle development, reproductive phase, and dormancy. The second table reports oxygen-release values for the same four species across four biomass-development stages: initial biomass, intermediate biomass, mature biomass, and aging biomass.

The graphical part of the dataset is broader than the two tables. Figure 1 includes phenological trajectories across four landscape examples: desert, pasture/rangeland, mountain, and foothill landscapes. Figure 2 presents biomass-stage trajectories across the same landscape examples. Figure 3 presents spectral signatures for eight species or species groups, including saxaul, tamarix, juniper, birch, maple, oak, pine, and almond. Figure 4 presents a correlation matrix linking oxygen release with canopy density, NDVI, LAI, and precipitation. Figures 5 and 6 present long-term species-level projections under RCP 4.5 and RCP 8.5.

This structure required careful interpretation. Tables 1 and 2 provide direct numerical values for four species, while Figures 1–6 represent an expanded dissertation figure series. Therefore, the article does not claim that all figure values are directly derived from Tables 1 and 2. Instead, the tables are used for transparent numerical comparison, and the figures are used as supporting evidence for landscape-specific trajectories, spectral response, correlation structure, and climate-scenario interpretation. Phenological assessment was based on four phases of tree development. Early development represents the beginning of active seasonal growth. Middle development represents the strongest canopy activity and peak photosynthetic potential. The reproductive phase represents a slightly reduced but still active stage. Dormancy represents the lowest activity period, when leaf loss or metabolic

slowdown sharply limits oxygen release. The values were interpreted using the ecological assumption that oxygen release is mainly controlled by photosynthetically active leaf area and canopy vigor (Cleland et al., 2007; Richardson et al., 2013).

Biomass-stage assessment was based on four structural stages: initial biomass, intermediate biomass, mature biomass, and aging biomass. The table values were used to compare how oxygen-release potential changes as trees move from early establishment to mature stand condition. The mature biomass stage was expected to produce the highest values because of greater canopy size, stronger leaf area, and higher biomass accumulation.

Remote sensing was incorporated through NDVI, LAI, canopy density, spectral response curves, and GIS-supported interpretation. Spectral signatures were used to show how different species reflect light across blue, green, red, near-infrared, and shortwave infrared bands. In vegetation analysis, high near-infrared reflectance and lower red reflectance are commonly associated with green vegetation structure and chlorophyll absorption, which explains why NDVI and related indices are useful for ecological monitoring (Huete et al., 2002; Pettorelli et al., 2005; Tucker, 1979).

The correlation matrix was interpreted as exploratory evidence. Because the dataset behind the matrix is not fully archived in the manuscript, the correlations were not used for causal claims. They were used only to show whether oxygen release tends to move together with canopy density, NDVI, LAI, and precipitation.

The scenario component used RCP 4.5 and RCP 8.5 pathways. RCP 4.5 was interpreted as a moderated pathway with improved management, sustained restoration, and lower climate pressure. RCP 8.5 was interpreted as a high-emissions and high-stress pathway. The projections were used to compare long-term divergence in oxygen-release potential to 2040, 2070, and 2100. These scenarios were not treated as exact forecasts. They were interpreted as scenario-based trajectories showing how oxygen-release potential may

respond under different climate and management conditions (Moss et al., 2010; Riahi et al., 2011; Thomson et al., 2011; van Vuuren et al., 2011).

3. Results

Table 1 shows that oxygen release differed strongly across phenological phases. Across the four species, the mean value increased from 135 kg ha⁻¹ yr⁻¹ during early development to 287.5

kg ha⁻¹ yr⁻¹ during middle development. This represents an increase of approximately 113%. The mean value then declined slightly to 270 kg ha⁻¹ yr⁻¹ during the reproductive phase and dropped sharply to 48.75 kg ha⁻¹ yr⁻¹ during dormancy. This means that mean oxygen release during dormancy was about 83% lower than during middle development.

Table 1. Oxygen-release values across phenological phases.

Species	Early development (kg ha ⁻¹ yr ⁻¹)	Middle development (kg ha ⁻¹ yr ⁻¹)	Reproductive phase (kg ha ⁻¹ yr ⁻¹)	Dormancy (kg ha ⁻¹ yr ⁻¹)
Oak	150	300	280	50
Pine	120	250	240	60
Birch	130	290	270	40
Plane tree	140	310	290	45

Table 1 demonstrates that the middle development phase is the strongest period for oxygen release in all four species. Plane tree recorded the highest middle-development value, 310 kg ha⁻¹ yr⁻¹, followed by oak, 300 kg ha⁻¹ yr⁻¹, birch, 290 kg ha⁻¹ yr⁻¹, and pine, 250 kg ha⁻¹ yr⁻¹. The reproductive phase remained high but slightly lower than the middle development phase. Dormancy produced the lowest values in all species, ranging from 40 kg ha⁻¹ yr⁻¹ in birch to 60 kg ha⁻¹ yr⁻¹ in pine. This confirms that phenological timing is critical for oxygen-release assessment. If field observation or satellite monitoring is conducted during dormancy, the ecological potential of a stand may be strongly underestimated.

Figure 1 presents the phenological trajectories from the expanded dissertation figure series. It shows the same general pattern across landscape examples: oxygen release rises from early growth to mid-growth, decreases slightly during reproduction, and falls sharply during dormancy.

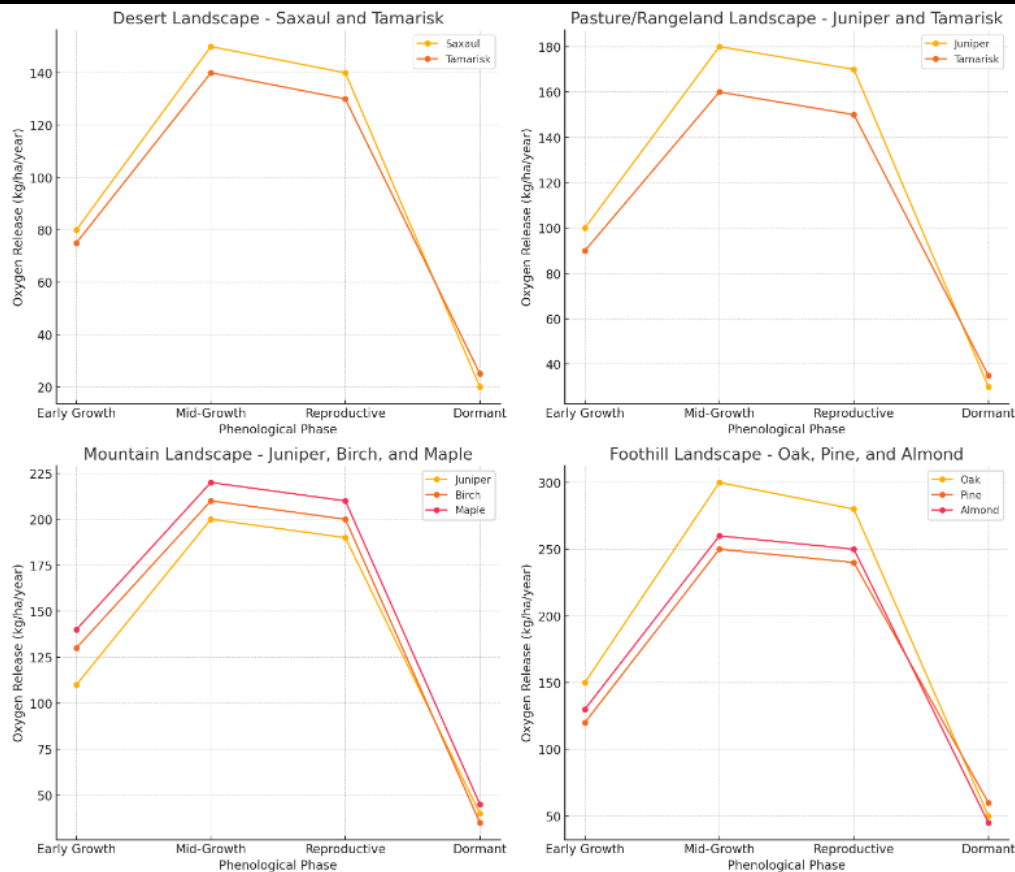


Figure 1. Species-level oxygen-release trajectories across phenological phases in selected landscape examples of Uzbekistan.

Figure 1 supports the main conclusion from Table 1 but adds a landscape dimension. In the desert panel, saxaul and tamarix show lower absolute values than the foothill panel, where oak, pine, and almond reach higher levels. The pasture/rangeland and mountain panels occupy an intermediate position. The important point is not only that species differ, but that all species follow a similar seasonal arc. Mid-growth is the most productive phase, while dormancy is the lowest-output phase. This means that GIS-based oxygen-release mapping should use comparable phenological windows. Otherwise, one region

may appear weaker simply because it was observed at a different seasonal stage.

Table 2 shows that biomass development has an even stronger effect than phenological phase. Mean oxygen release increased from 98.75 kg ha⁻¹ yr⁻¹ at the initial biomass stage to 202.5 kg ha⁻¹ yr⁻¹ at the intermediate biomass stage and 337.5 kg ha⁻¹ yr⁻¹ at the mature biomass stage. The mature biomass stage produced approximately 242% more oxygen than the initial biomass stage. During aging biomass, the mean value declined to 175 kg ha⁻¹ yr⁻¹, which is about 48% lower than the mature stage.

Table 2. Oxygen-release values across biomass-development stages

Species	Initial biomass (kg ha ⁻¹ yr ⁻¹)	Intermediate biomass (kg ha ⁻¹ yr ⁻¹)	Mature biomass (kg ha ⁻¹ yr ⁻¹)	Aging biomass (kg ha ⁻¹ yr ⁻¹)
Oak	100	200	350	180
Pine	90	180	300	160
Birch	95	210	340	170
Plane tree	110	220	360	190

Table 2 confirms that oxygen-release potential depends heavily on structural development.

Plane tree recorded the highest mature biomass value, 360 kg ha⁻¹ yr⁻¹, followed by oak, 350 kg

ha⁻¹ yr⁻¹, birch, 340 kg ha⁻¹ yr⁻¹, and pine, 300 kg ha⁻¹ yr⁻¹. Initial biomass values were much lower, ranging only from 90 to 110 kg ha⁻¹ yr⁻¹. The aging stage did not collapse as sharply as dormancy in Table 1, but it still showed a clear decline compared with the mature stage. This means that afforestation success should not be evaluated only by planting. Survival, stand development, canopy expansion, and transition to mature biomass are more important for long-term oxygen-release potential.

Figure 2 presents biomass-development trajectories across the expanded landscape examples. The figure shows that mature biomass is the highest-output stage in each landscape panel, while initial and aging stages are lower.

Figure 2 shows that oxygen release increases strongly as stands move from initial biomass to mature biomass. The desert panel has lower values than the foothill and mountain panels, which is expected because desert vegetation faces stronger moisture and heat constraints. The foothill panel shows the highest mature biomass values, especially for oak. This figure supports an important management conclusion: ecological benefits from tree planting are delayed. Newly planted trees may survive but still provide limited oxygen-release potential until they develop sufficient biomass and canopy structure. Therefore, long-term maintenance is as important as initial planting.

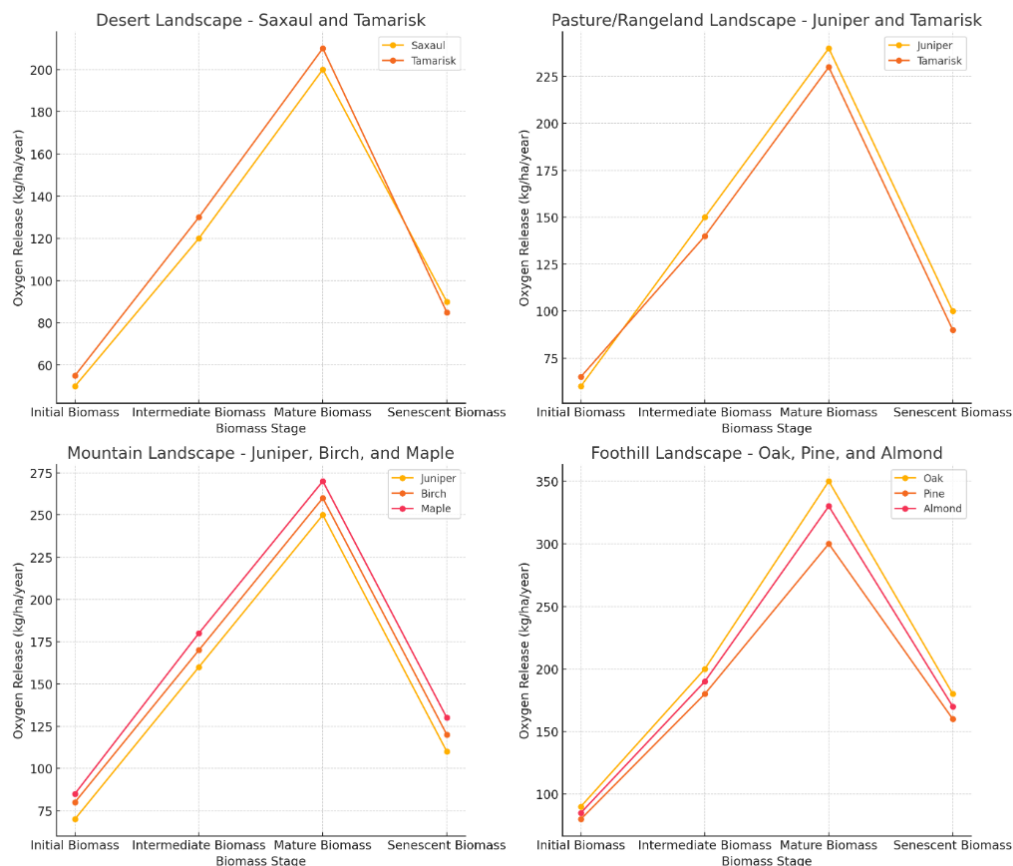


Figure 2. Species-level oxygen-release trajectories across biomass-development stages in selected landscape examples of Uzbekistan.

Figure 3 presents spectral signatures for eight species or species groups: saxaul, tamarix, juniper, birch, maple, oak, pine, and almond. In the original draft, this figure was described as an additional biomass-stage visualization, but that caption was not accurate. The figure actually shows reflectance across spectral bands.

Figure 3 shows that all species have low reflectance in the blue and red bands and higher reflectance in the near-infrared band. This pattern is typical for green vegetation because chlorophyll absorbs visible red light while internal leaf structure reflects near-infrared radiation. The spectral curves therefore provide

a remote-sensing basis for using NDVI and related vegetation indices in oxygen-release assessment. The figure does not directly measure oxygen release. Its role is to show that

different species can be identified or compared through spectral behaviour, which can then support GIS-based mapping of vegetation condition and productivity.

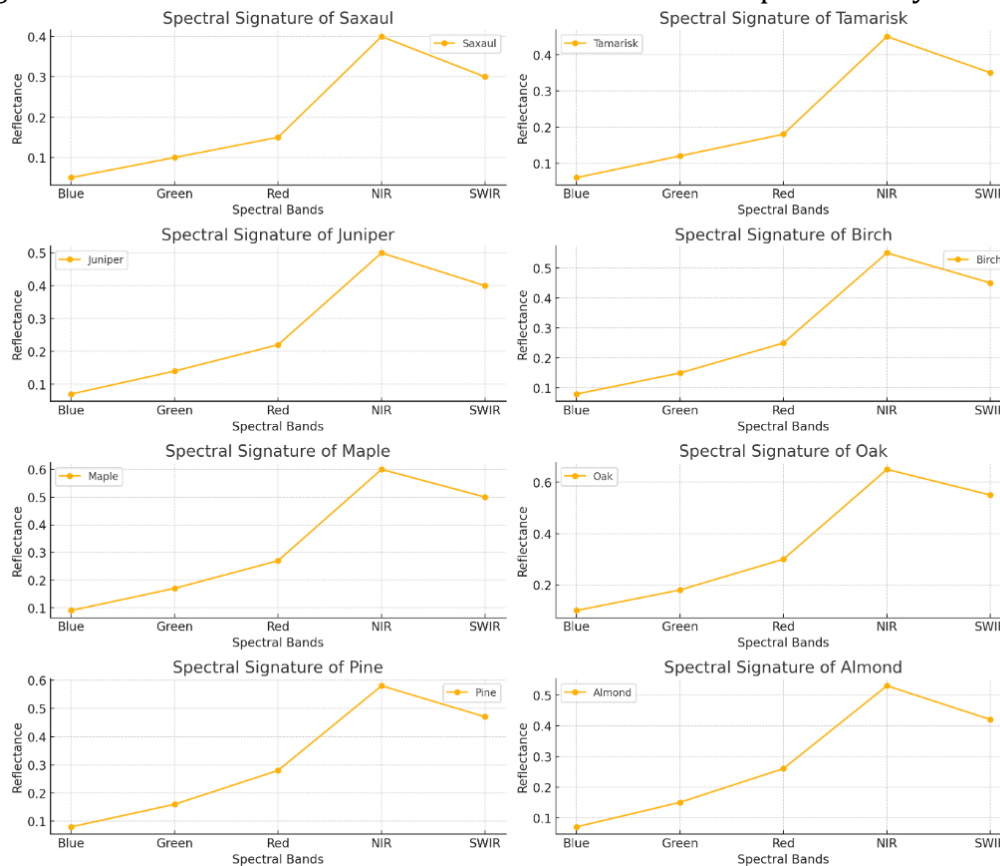


Figure 3. Spectral signatures of selected tree species and restoration groups used for remote-sensing interpretation of vegetation condition.

Figure 4 presents the correlation matrix among oxygen release, canopy density, NDVI, LAI, and precipitation. The matrix shows that oxygen release has a weak positive correlation with NDVI, $r = 0.27$, and LAI, $r = 0.18$. Its relationship with canopy density is slightly negative, $r = -0.06$, and its relationship with precipitation is nearly zero, $r = -0.01$. NDVI and LAI show a stronger positive relationship, $r = 0.45$.

Figure 4 is important because it shows that the current correlation evidence is exploratory rather than conclusive. The positive relationship between oxygen release and NDVI is ecologically meaningful, since NDVI usually

reflects vegetation greenness and photosynthetic activity. The positive relationship with LAI is also expected because greater leaf area generally supports higher photosynthetic capacity. However, the low correlation with precipitation and the weak negative value for canopy density suggest that the dataset may be small, mixed across landscapes, or influenced by other variables such as species, stand age, salinity, temperature, or management condition. Therefore, the heatmap should be discussed as a preliminary diagnostic tool, not as final statistical proof.

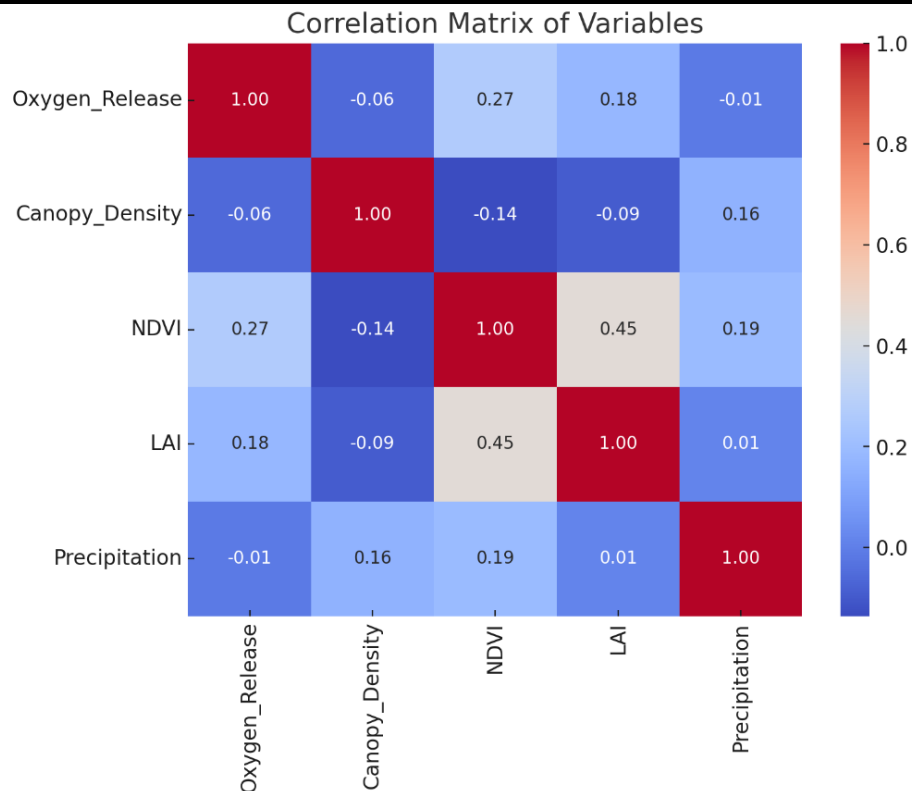


Figure 4. Correlation matrix among oxygen release, canopy density, NDVI, LAI, and precipitation.

Figures 5 and 6 show long-term oxygen-release projections under two climate pathways. Figure 5 represents the RCP 4.5 pathway. In this scenario, most species show increasing oxygen-release values from 2023 to 2100. The general direction suggests that ecological management, restoration, and moderated climate pressure can maintain or improve tree oxygen-release potential.

Figure 5 indicates a generally positive trajectory for oxygen release under the moderated scenario. Species with higher baseline values,

such as oak and pine, continue to perform strongly by 2100, while lower-output desert species also improve gradually. The figure should be interpreted as a scenario-based planning tool rather than a precise forecast. Its value is that it shows how oxygen-release potential may increase when restoration, management, and climate mitigation reduce stress on vegetation systems.

Figure 6 represents the RCP 8.5 pathway. Under this scenario, most species show declining oxygen-release values after 2040 or 2070. Some species show slight early increases, but the long-term direction is downward by 2100.

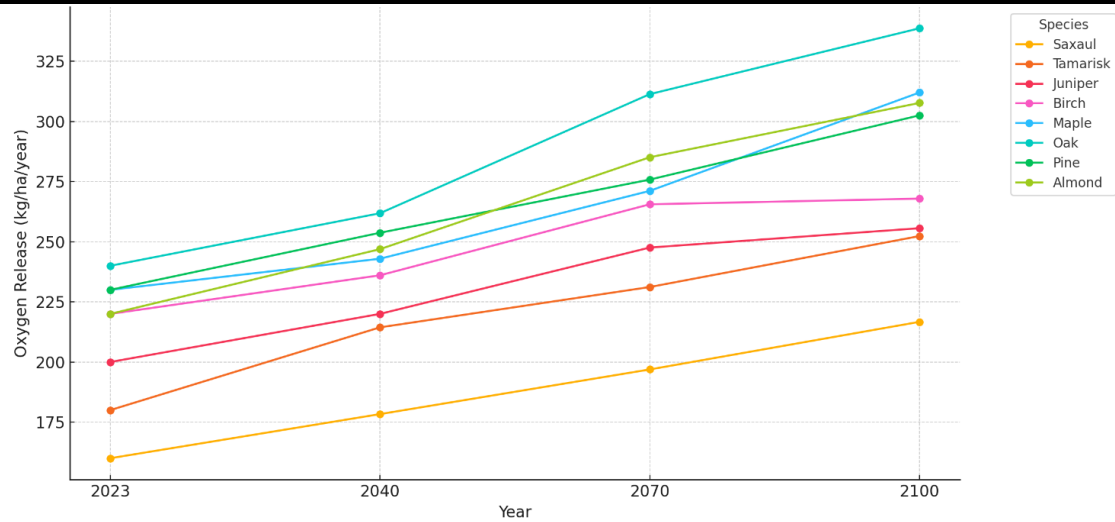


Figure 5. Projected species-level oxygen release under RCP 4.5 through 2100.

Figure 6 demonstrates the risk of long-term decline under stronger warming and degradation pressure. The decline is not identical for all species, which suggests differences in ecological tolerance and landscape suitability. Desert-adapted species may remain relatively stable at low levels, while higher-output species may lose performance

more sharply under stress. The figure supports the conclusion that climate adaptation and restoration policy are directly connected to the future ecological value of tree stands. Without management, oxygen-release potential may decline even in areas where present-day vegetation appears productive.

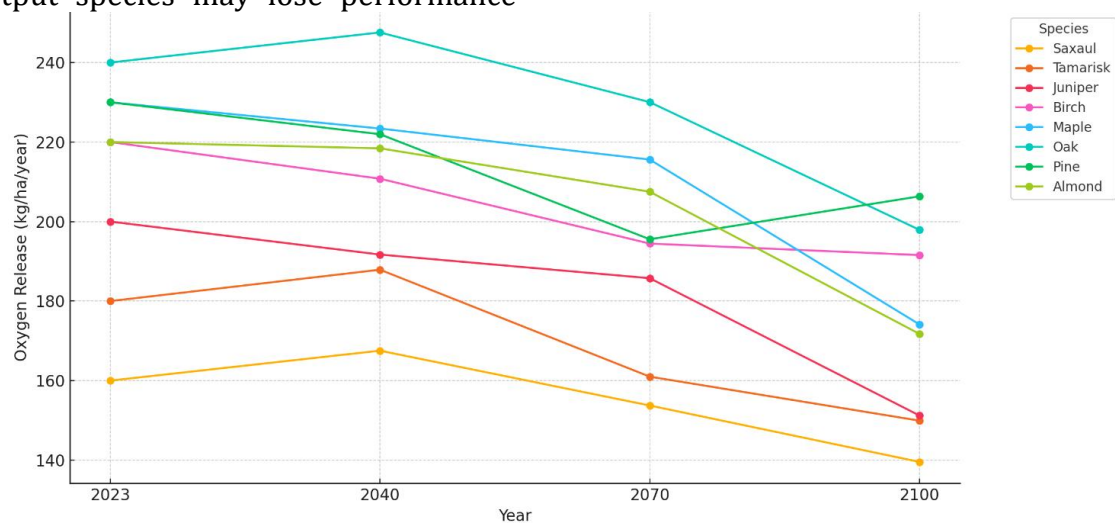


Figure 6. Projected species-level oxygen release under RCP 8.5 through 2100.

The optimistic scenario implies that oxygen release is policy-responsive: long-term ecological intervention can preserve or even expand this ecosystem service. The pessimistic scenario demonstrates the opposite. The dissertation notes that by 2100, the loss of high-output taxa in vulnerable landscapes would significantly reduce ecological functionality. Thus, oxygen release acts as a sensitive

integrative metric of forest condition, climate adaptation, and restoration effectiveness.

4. Discussion

The results show that oxygen release is controlled by three connected time scales. The first is seasonal time, represented by phenological phases. The second is stand-development time, represented by biomass stages. The third is long-term climate time, represented by RCP-based projections to 2100.

This three-scale structure is the main scientific strength of the article. It shows that oxygen release is dynamic, not static.

The phenological results confirm that middle development is the most productive phase. This is consistent with the biological logic of active leaf area and high photosynthetic capacity. The sharp decline during dormancy shows why oxygen-release monitoring must be seasonally standardized. Comparing regions or species without controlling for phenological phase may produce misleading results. For example, a mature and productive stand observed during dormancy may appear weaker than a less productive stand observed during peak growth. The biomass results show that mature stands provide the highest oxygen-release potential. This has direct policy relevance. In many restoration programs, success is measured by planting numbers or total planted area. However, Table 2 and Figure 2 show that early-stage biomass has much lower oxygen-release values than mature biomass. Therefore, restoration monitoring should include survival rate, canopy closure, NDVI/EVI trajectory, biomass development, and stand maturity. Planting without long-term maintenance will not produce the expected ecological services.

The spectral-signature figure strengthens the GIS and remote-sensing argument. Since different tree groups show clear reflectance patterns, remote sensing can support species or vegetation-type interpretation. The strong near-infrared response shown in Figure 3 also justifies the use of NDVI and related vegetation indices. Still, the manuscript should avoid claiming that spectral signatures directly calculate oxygen release. They only help identify vegetation condition and support spatial estimation when combined with ecological coefficients.

The correlation matrix provides useful but limited evidence. Oxygen release is positively related to NDVI and LAI, but the correlation values are not strong. This may reflect mixed species, mixed landscapes, limited sample size, or the absence of variables such as salinity, stand age, soil moisture, and canopy health. For a stronger Scopus-level paper, the authors

should add the raw dataset, specify the number of observations, and run regression or mixed-effect modelling. At the current stage, Figure 4 should be interpreted as a preliminary correlation summary.

The climate-scenario results give the article a forward-looking contribution. Under RCP 4.5, oxygen-release values increase, which suggests that ecological intervention and moderated climate forcing can improve vegetation services. Under RCP 8.5, the decline by 2100 shows that unmanaged warming, degradation, and weaker restoration control may reduce oxygen-release potential. This scenario contrast is useful for communicating the importance of restoration policy, although it should be presented as a scenario-based projection rather than a deterministic prediction.

For Uzbekistan, the findings are relevant to afforestation, urban greening, mountain and foothill forest conservation, and restoration of degraded drylands. However, oxygen release should not be presented as the only benefit of trees. In dryland and semi-arid regions, tree planting is often more important for soil stabilization, dust reduction, carbon sequestration, microclimate regulation, and landscape resilience. Oxygen-release potential is therefore best used as one ecological productivity indicator within a broader ecosystem-service framework.

5. Conclusion

This article assessed tree oxygen release dynamics in Uzbekistan using phenological, biomass, spectral, correlation, and climate-scenario evidence. The results showed that oxygen release changes strongly across biological and climate time scales. In the phenological table, mean oxygen release increased from 135 kg ha⁻¹ yr⁻¹ during early development to 287.5 kg ha⁻¹ yr⁻¹ during middle development, then declined to 48.75 kg ha⁻¹ yr⁻¹ during dormancy. In the biomass table, mean oxygen release increased from 98.75 kg ha⁻¹ yr⁻¹ at the initial biomass stage to 337.5 kg ha⁻¹ yr⁻¹ at mature biomass, before falling to 175 kg ha⁻¹ yr⁻¹ during aging.

The figures supported the same interpretation. Phenological trajectories showed the

dominance of mid-growth stages, biomass trajectories showed the importance of maturity, spectral signatures justified the use of remote-sensing vegetation indicators, and the correlation matrix showed a preliminary positive association between oxygen release, NDVI, and LAI. The RCP 4.5 scenario suggested long-term improvement under managed and moderated conditions, while RCP 8.5 showed possible decline under high climate stress.

The study concludes that oxygen-release assessment can be useful for ecological monitoring in Uzbekistan, but only when interpreted carefully. It should be linked to phenology, biomass, canopy condition, species composition, and climate scenario. Future research should expand the plot-level dataset, clarify the oxygen-release calculation equations, validate species-specific coefficients, and integrate GIS-based oxygen-release mapping with NDVI, EVI, LAI, biomass, salinity, temperature, and precipitation layers.

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