



# Brief Communication: RxGaming- A Flexible Open-Source Tool Using Aerial Lidar to Incorporate Tree Spatial Patterns in Mechanical Treatments

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## Abstract

Dry forest ecosystems in the western United States face the pressure of uncharacteristically severe wildfires and widespread drought-induced mortality as a result of fire exclusion, past management practices, and climate change. Implementing forest treatments that incorporate individual tree, clump, and opening (ICO) patterns can help to increase forest resilience to these disturbances. We explore tradeoffs in meeting treatment goals while incorporating ICO concepts in a case study using RxGaming, a publicly available, open-source software tool. The RxGaming tool provides a framework for decision making via 1) visualization and assessment of current stand structure and 2) treatment simulations using an algorithm that incorporates ICO-based thinning methods and reflects user-defined objectives.

**Keywords** Lidar · ICO patterns · Tool · Fuels · Restoration

## Introduction

As wildfires and drought severity increase in dry and historically frequent-fire conifer forests of the western US (“dry forests”), there is a growing need for proactive management to improve forest resilience to these disturbances (North et al. 2009; Coop et al. 2020; Cova et al. 2023). Past research has found fine-scale, within-stand patterns of tree clumps and openings in reconstructions of historical fire-resilient

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stands and in contemporary forests with restored fire regimes (Lydersen et al. 2013; Chamberlain et al. 2023a, b). Forest managers increasingly are seeking to replicate these patterns when implementing mechanical thinning, fuels reduction, and prescribed fire treatments (Churchill et al. 2013; Olszewski et al. 2022).

One widely adopted method to incorporate these spatial patterns into treatments is the ICO (Individual trees, Clumps, and Openings) approach, which quantifies the distributions of clump and opening sizes (ICO patterns) in a way that is usable by field personnel. ICO patterns provide scientists and managers with guidelines for implementing restoration treatments that improve resilience to wildfire, drought, pathogens, insect outbreaks, and climatic variability while also improving habitat quality, snow water retention, and regeneration of shade-intolerant tree species (Larson and Churchill 2012; Churchill et al. 2013; 2016; 2017; Wiggins et al. 2019; Ritter et al. 2020; Chamberlain et al. 2023a, b).

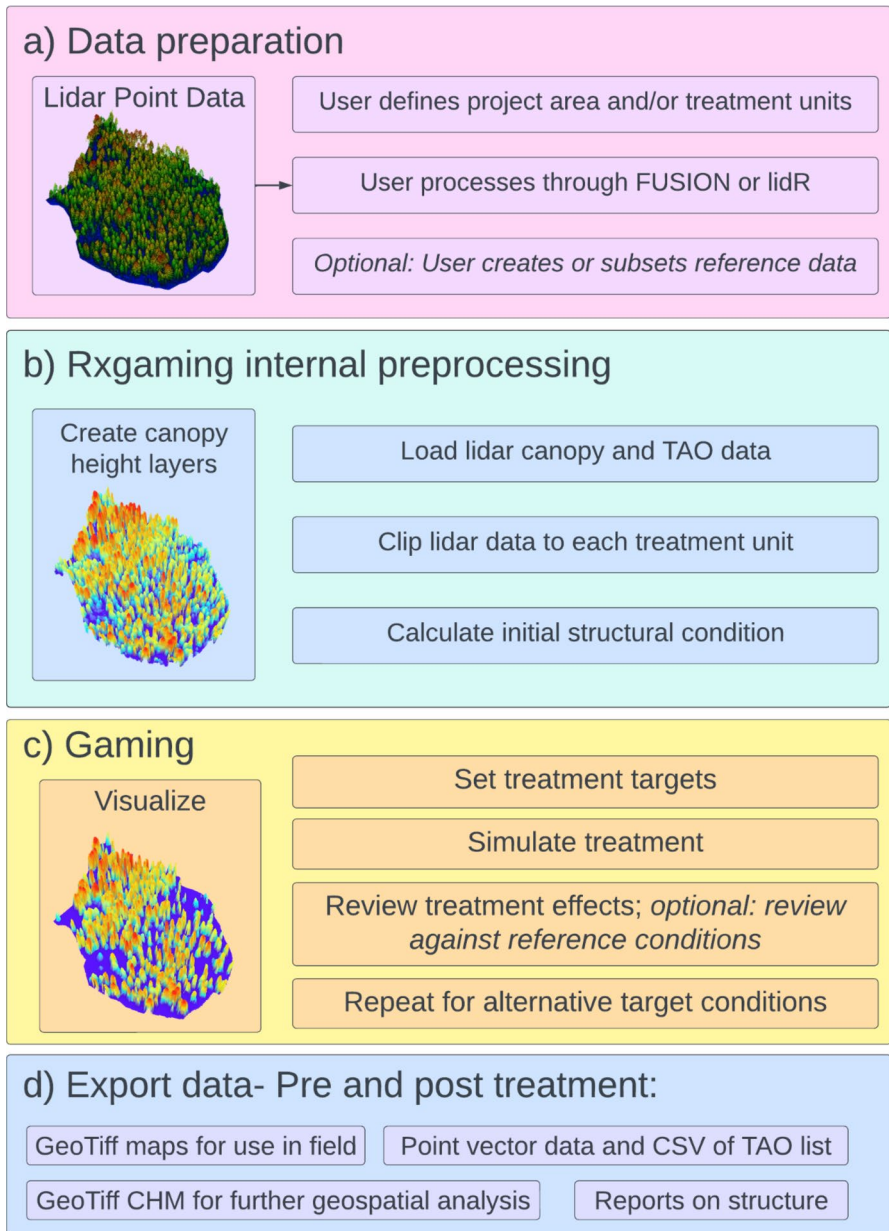
Reference conditions reflecting the natural range of variability of forest structure and fine-scale tree spatial patterns at the stand to watershed scale are available for many frequent-fire forest types. When analyzed in the context of anticipated climate change, reference conditions serve as a template for restoration treatments (Fulé et al. 1997; Keane et al. 2009; Sánchez Meador et al. 2011; Churchill et al. 2013; 2017; Brown et al. 2015; Clyatt et al. 2016; LeFevre et al. 2020). However, when using reference conditions, managers commonly report challenges visualizing and incorporating ICO concepts into their treatment planning due to the time and expense of measurement, conflicting objectives, and difficulty communicating with stakeholders.

Here, we describe a new open-source tool for Windows computers- RxGaming- that simplifies and expedites planning of thinning treatments integrating ICO spatial patterns and reference conditions, using aerial lidar data. We then demonstrate the tool in a case study showing how to address challenges in ICO-based treatment planning.

## Methods

We designed the RxGaming tool to be used without requiring specialized knowledge such as expertise manipulating aerial lidar data or performing geospatial analyses. The tool provides users with calculations and visualizations of project area (a collection of stands) forest structure before and after simulated treatments and provides a framework to compare these against supplied desired or reference conditions. Practitioners can run multiple alternative simulation to explore the best balance among goals and combine these with in-the-field observations when developing final treatment plans. Tool outputs can inform prescriptions and implementation (Fig. 1).

RxGaming complements common ICO treatment planning methods while addressing their limitations, such as the difficulty envisioning the cumulative effects of proposed treatments across large project areas. It supplements essential field observations by analyzing, visually displaying, and simulating treatments over project areas.



**Fig. 1** Flow chart describing the general function and control flow of the RxGaming tool. Discrete stages are labeled a-d, with each section containing information about actions that occur during that stage. TAO: tree approximate object; CHM: canopy height model; CSV: comma-separated values. Created using Lucidchart

The tool assesses treatment units based on four metrics measured with aerial lidar data (in metric units for publication; the tool uses imperial units natively): basal area

(BA), density (overstory trees per hectare [TPH]), canopy cover (CC), and mean clump size (MCS) (Ma et al. 2017; Churchill et al. 2017; Chamberlain et al. 2023a, b). This allows users to design treatments that affect multiple important overstory structural components simultaneously.

Full descriptions for the use of the tool can be found in its manual provided as a supplement to this paper (hereafter S1).

### **Input Data: Treatment Units and Aerial Lidar Data**

The user provides a shapefile identifying the boundaries of one to multiple treatment polygons within a project area and processed aerial lidar data. Aerial lidar data can be used to visualize and quantitatively analyze forest spatial patterns including ICO patterns (Kane et al. 2019; Wiggins et al. 2019; Olszewski et al. 2022). Maps of lidar-identified overstory trees provide an analog to field-derived stem maps of overstory trees. RxGaming uses outputs derived from lidar point clouds created with the USDA Forest Service (Forest Service) FUSION or the R package “lidR” processing tools (Roussel et al. 2020; Mcgaughey 2022). Overstory trees are identified using FUSION or lidR’s canopy surface model and tree segmentation routines. We refer to these identified trees as tree approximate objects (TAOs) to acknowledge that they often represent multiple trees—the dominant tree plus any unseen co-dominant and/or understory trees (Jeronimo et al. 2018). Because TAOs are a primary data input, relatively high-density lidar data is required ( $\geq 8$  pulses  $\text{m}^{-2}$ ).

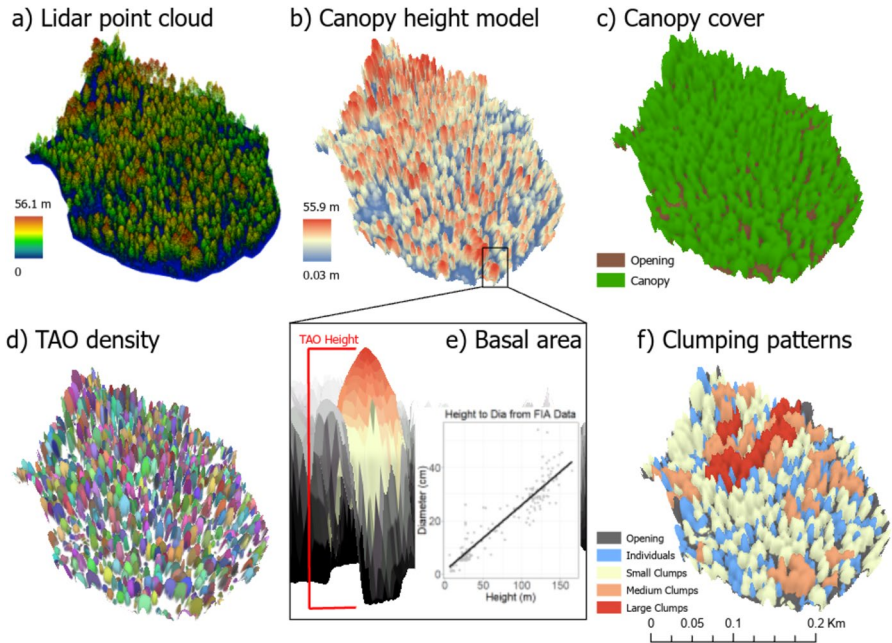
### **Measuring Forest Structure**

RxGaming analyzes treatment units based on four metrics of forest structure derived from the lidar CHM and TAOs (Fig. 2). Past research has shown that these measurements are relevant to management, acknowledging that they differ from field methods which can also measure the understory.

1. Basal area—(see below).
2. TAOs per hectare— density of the TAOs in the treatment unit.
3. Canopy cover – the ratio of the area of the CHM  $> 2$  m in height (representing the overstory) divided by the area of the treatment unit and presented as a percent (Ma et al. 2017; Kane et al. 2019).
4. Mean clump size and the clump size distribution (CSD) – (see below).

### **TAO Diameters and BA Allometry**

To calculate TAO DBH from lidar derived heights, the tool searches the Forest Service Forest Inventory and Analysis plot database (Gray et al. 2012) for all plots local to the project area. Using the subset of trees that have both their true heights and



**Fig. 2** Isometric visualizations of different lidar derived data structures or metrics that the RxGaming tool uses for input or calculates. **a** The raw lidar point cloud that all metrics are based on, colored by height above ground; **b** 0.75 m resolution canopy height model created from the point cloud; the overstorey canopy is segmented into overstorey tree approximate objects (TAOs) using a watershed segmentation algorithm; **c** Canopy cover (CC) defined as the area in the canopy model above 2 m divided by the total area in the area of interest; **d** TAO density (TPA/TPH) defined as the number of TAOs representing overstorey trees per unit area; **e** Basal area (BA) per unit area. Diameter is derived from TAO height through allometric regressions defined on local FIA plots. TAO basal area and total BA per unit area can be further derived from the regressed diameter; **f** Clumping patterns derived from TAOs—TAOs are considered clumped if their inter-tree high point to high point distance is < 6 m. TPA: trees per hectare; TPH: trees per hectare; FIA: Forest inventory analysis. Created using ESRI ArcPro

diameters measured in the field, RxGaming fits a linear model using the transformation (none, square root or cube root response transforms, or log–log) that results in the lowest root mean squared error (Kane et al. 2023).

TAO DBHs are used to 1) define a DBH limit above which TAOs will be retained when simulating treatment effects and 2) estimate overstorey BA as the sum of the areas at breast height of all TAOs identified in the lidar data.

### Mean Clump Size

We based our measurements of clumping patterns on the ICO methodology established by Churchill et al. (2013). Following past research, we used a fixed radius of 3 m for each TAO (e.g. Ritter et al. 2020).

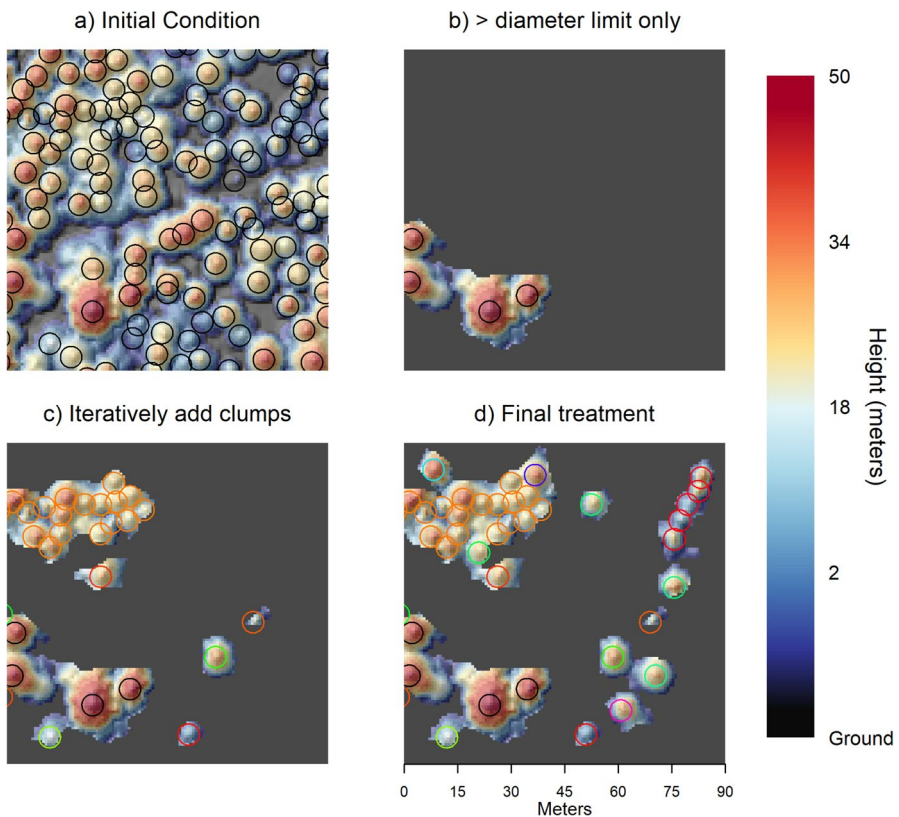
TAO “A” is considered clumped with TAO “B” if their inter-tree distance is less than 6 m (i.e. the fixed crown radii overlap). Clump membership percolates so that

any other TAOs clumped to TAO “B” are also considered clumped with “A.” Each TAO is assigned a clump size value equal to the number of TAOs in its clump. Thus, the MCS is calculated from the CSD of a given treatment unit.

RxGaming translates the user-defined MCS target to a clump size distribution via a lookup table (described in S1). This table describes the mean proportion in different clump size classes for ranges of MCS as observed empirically by Jeronimo et al. 2019.

## Reference Conditions

Users can optionally input a reference dataset to RxGaming, which will display a graphical visualization of those conditions in comparison with treatment units. Decisions based on these visualizations can be entered as treatment targets by the



**Fig. 3** Visualizations of the canopy height model and modeled TAO crown radii (superimposed circles). **a** Initial condition shows all the TAOs as captured by the lidar data. **b** All TAOs < diameter limit removed as initial step of treatment simulation. **c** Visualization of treatment algorithm reintroducing clumps of trees midway through simulation. Superimposed crown radii are colored by the discrete step in which the TAOs were added back into the CHM. **d** Visualization of CHM upon simulation completion. Crown radii colored with the same method as described for panel c. Created using R

user. This flexible framework assists users in determining desired conditions. This tool was originally designed with wildfire resilience in mind, but will work with datasets that define different desired conditions (e.g. drought resilience, snow water retention, pathogen resilience, wildlife habitat) provided those structural conditions can be achieved with removal of trees to create spatial patterns (Kaufmann et al. 1998; Moore et al. 1999).

A database of reference areas for mixed conifer stands with active fire regimes in the Sierra Nevada derived from Chamberlain et al. (2023b) is provided. Users can provide a different database, so long as it includes the metrics described in Section "Reference Conditions" and is formatted as described in S1.

## Treatment Thinning Algorithm

The goal of the treatment thinning algorithm is to simulate removal of TAOs in a way that is theoretically operationally possible to apply in the field. We designed the algorithm to meet the BA target objective, to create a CSD that best matches the target CSD, and to use a clump of trees as the fundamental unit. The objective is not to provide a treatment prescription for direct implementation but rather to allow efficient visualization and exploration of spatially explicit overstory thinning options.

The algorithm starts by retaining all TAOs above the defined diameter limit, then iteratively selects clumps of TAOs to be retained until the BA target is met. The algorithm is weighted toward retaining trees with larger diameters. When selecting clump sizes to create, it chooses sizes that best align the resultant CSD against the target CSD. A visualization of the algorithm is represented in Fig. 3 (details in S1).

## RxGaming Outputs

RxGaming produces a suite of outputs for each treatment unit representing both pre-treatment and simulated post-treatment conditions. These outputs include:

1. Tables of pre-treatment, target, and post-treatment conditions.

**Table 1** Potential challenges managers might encounter in the treatment planning process and descriptions of how the RxGaming tool can provide decision support in those scenarios. CC: Canopy cover

Treatment problem	Use RxGaming to explore prescriptions that...
Even age stand—young	...introduce clumps and openings in the context of future growth and/or treatments
Even age stand—mature	...introduce clumps and openings based on current stand conditions
Multi age, dense stand	...reinforce existing heterogeneity, reduce density
Habitat quality (CC limit)	...investigate tradeoffs at different CC levels and use the outputs to communicate with stakeholders
Many large trees (Diameter limit)	...investigate tradeoffs at different diameter limits and use the outputs to communicate with stakeholders

**Fig. 4** Information regarding the case study. **a** Study site location and Lake Tahoe Basin Management Unit boundary within the Sierra Nevada Ecoregion, California. **b** Structure metrics for the untreated condition as well as treatment scenario targets and resultant structure, with changed targets highlighted. **c** Visualization of the stand in the initial untreated condition (i), results of treatment scenario 1 (ii), and results of treatment scenario 2 (iii). **d** Comparison of the RxGaming tool's current, target, and simulated treatment structure values against reference area structure values. Current structure (blue triangle), target structure (squares) for two different treatment scenarios (green and purple), and simulated treated structures (circles) are connected via a grey line. Background 2d kernel density estimates in orange show structure metric distributions for reference sites representing the same climate class as the case study site, which can be a tool for informing treatment targets. Targets and results have been fuzzed where they overlap for visual clarity. Sections b, c, and d are RxGaming tool outputs, arranged for publication. Results are presented in metric, though the RxGaming tool uses imperial. Imagery from ESRI World Imagery base layer which sources imagery from Maxar, USGS, and Earthstar Geographics. DL: diameter limit (cm); BA: basal area ( $\text{m}^2\text{ha}^{-1}$ ); MCS: mean clump size (n trees); CC: canopy cover (percent). Created using ESRI ArcPro, Python, RxGaming, Microsoft paint, and Microsoft Powerpoint

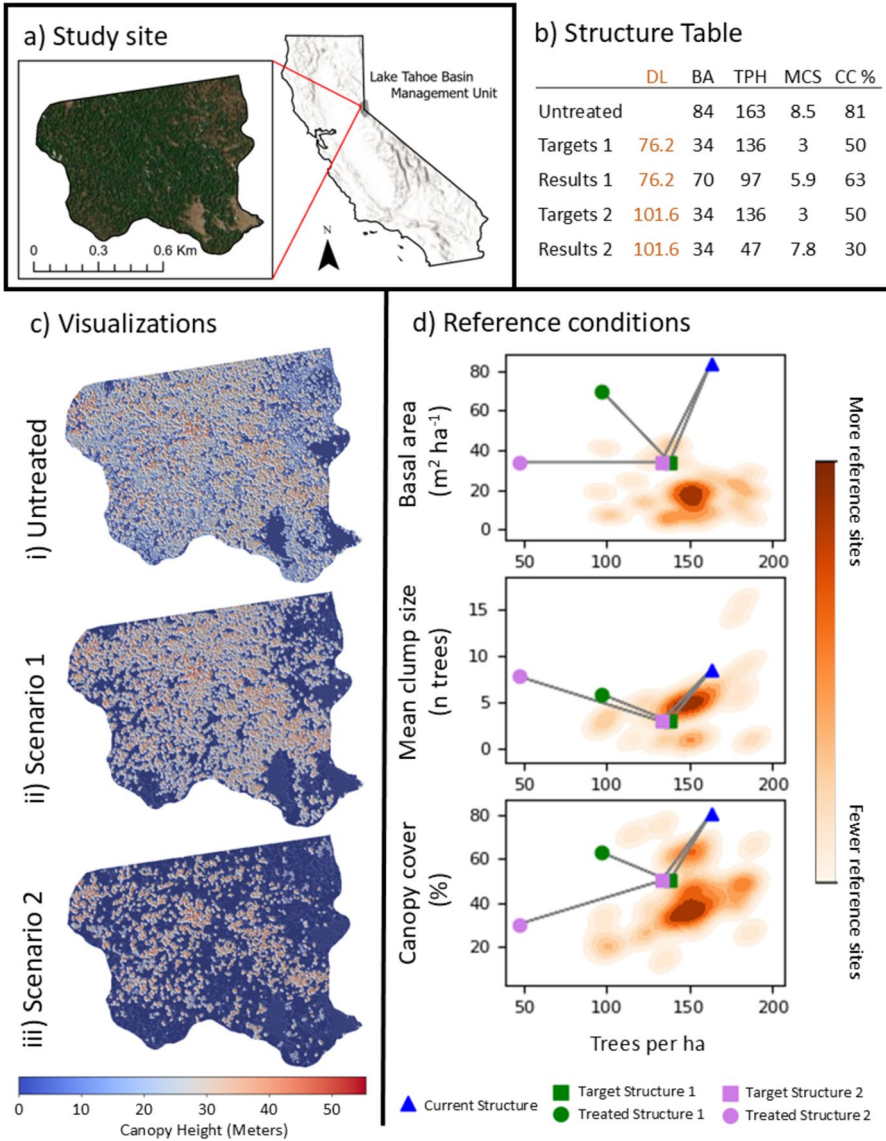
2. Density graphs of reference area condition with pre-treatment, target, and post-treatment condition overlaid
3. CSV TAO lists and shapefile point data of pre- and post-treatment TAOs
4. Density distributions describing pre- and post-treatment CSD and BA as well as BA distributions for removed TAOs.
5. Rasters and geo-pdf maps of the pre- and post-treatment canopy height model. These can be examined either in GIS packages in the office or transferred to tablets or phones for use in the field.

## Case Study

We outline the RxGaming tool's ability to address common treatment problems in Table 1 and provide an example case study here (Fig. 4) with additional details and two other case studies in S1. We compared current and simulated treatment conditions against climatically and geographically matched reference conditions (Section 2.2; Chamberlain et al. 2023a, b). For each site, we evaluated two treatment scenarios which were designed based on personal communications with managers actively involved in planning these projects and structural patterns derived from Sierra Nevada reference sites.

The case study, situated in the Tahoe Basin West Shore WUI Healthy Forest and Fuels Reduction Project, was characterized by a low intensity harvest history (personal communication; Brian Garrett, Asst. Vegetation Management Staff Officer, Tahoe National Forest, Lake Tahoe Basin Management Unit), resulting in high BA and density. BA and CC were highly departed from reference conditions, while MCS was slightly higher than reference conditions. The site had a high proportion of existing large trees  $> 76.2$  cm (30") DBH, contributing to the high BA.

Both treatment scenarios centered around a significant reduction in BA with additional goals to reduce clump sizes and canopy continuity, while retaining as many large trees as possible. The scenarios used the same BA targets but differed in their



diameter limit threshold. Scenario 1 used the ecoregion standard of 76.2 cm (30") and scenario 2 explored a 101.6 cm (40") limit.

Scenario 1 was unable to achieve the BA target due to the diameter limit (too many TAOs with >76.2 cm DBH). Although it reduced CC to 56%, this remained high compared to reference conditions. This simulation resulted in the creation of a few larger openings, but much of the stand retained high canopy continuity.

Scenario 2 allowed for the removal of larger TAOs to meet the BA target and create an MCS of 7.9 and a CC of 30%, approximating reference conditions. Openings

were more dispersed in this simulation. While relaxing the diameter limit allowed the treatment algorithm to remove larger TAOs, it is designed to retain as many as possible. This allowed the algorithm to break up larger clumps of TAOs that may have caused challenges otherwise. Both treatments reduced the TPH of the stand well below that observed in the reference sites, indicating that there were more large trees in this site than observed in the reference sites.

Sites where large trees are abundant pose a rare challenge to foresters in this ecoregion (Kane et al. 2023). Large trees are of high ecological and social importance, therefore the decision to remove them requires careful consideration (Lutz et al. 2012; 2013; North et al. 2017; Kramer et al. 2021). Removing larger trees may be particularly controversial with wildlife biologists and public stakeholders. However, retaining all large trees may leave the stand with high leaf area and high canopy fuel connectivity, thus lacking resilience to subsequent disturbances and climate change (Agee and Skinner 2005). As demonstrated here, RxGaming simulations can assist decision makers and stakeholders understand the costs and benefits of different treatment outcomes, and their effects on large trees and associated values.

## Discussion

We designed RxGaming to address the growing need for ICO focused treatments, streamlined methods to operationalize lidar data, and tools to assist managers in understanding tradeoffs involved in silvicultural prescriptions. RxGaming can be used to assess conflicting objectives requiring both critical analysis of potential treatment effects and value-based judgements about the desired outcome of treatments, as demonstrated in the case study. We believe the tool could be valuable for managers working to restore dry forest landscapes, testing alternatives in the National Environmental Protection Act assessment process, and designing prescriptions. In past projects, users have found that visualizations of treatments produced by the RxGaming tool allowed them to communicate with internal and external stakeholders to understand the impacts of different treatment options. By assisting managers in incorporating ICO structural components in their treatments, RxGaming can promote resilience of dry forest ecosystems. We do not recommend setting prescriptions solely from the results of RxGaming simulations, but rather incorporating them alongside other data sources (e.g. stand exam data) that influence decision making (for example, when creating designation by prescriptions protocols).

## RxGaming Limitations

Lidar data and RxGaming have limitations that must be considered. First, lidar data primarily measures overstory structure and therefore assessments made through RxGaming are primarily representative of dominant trees. Surface and ladder fuels play a critical role in forest resilience and can have a major impact on fire behavior and severity (Agee and Skinner 2005; Battaglia et al. 2008; Prichard et al. 2010).

Because metrics derived from a CHM do not measure those features, additional assessment and interventions (e.g. prescribed fire) to address this component of restoration must be made. Second, lidar is unable to easily measure species, and therefore RxGaming allows for species-agnostic assessments only.

## Conclusion

Under ongoing demands to increase the pace and scale of treatments while incorporating additional ecological objectives integrating lidar data, forest structural modeling, and ecological theory (e.g. the ICO approach) can help managers efficiently understand the impacts of simultaneous objectives. RxGaming allows for straightforward comparison of stand conditions against reference conditions describing desired structure. With wide scale investment in high-resolution aerial lidar from state and national entities in the United States and the potential for future features (e.g. volume/merchantable timber estimates, wildlife/openings objectives, monitoring, implementation support), we believe the utility of this tool will grow over time. This tool will likely be increasingly valuable in assisting managers and stakeholders in making more informed and ecologically centered decisions regarding dry forest management in the twenty-first century.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s44392-025-00059-4>.

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**Authors Contributions** • Bryce N. Bartl-Geller was the lead author for this paper, created the figures, and was the primary developer for RxGaming.

- Caden Chamberlain provided methodological insight and extensive assistance writing and editing the paper as well as assisted in figure creation.
- Jonathan T. Kane was a developer on RxGaming and provided methodological input.
- Sean Jeronimo was involved in the conception of RxGaming, provided insight throughout its development, and the work described here builds upon his publications and dissertation.
- Liz Van Wagendonk assisted in editing and structuring the text.
- Van R. Kane was the principal investigator for the project and provided guidance and input at every stage.

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**Data Availability** Source code for RxGaming is found at <https://bitbucket.org/rrams/rxgaming/src/main/>

Downloads for compiled versions of RxGaming and Sample data are found at <https://drive.google.com/drive/folders/1wGfARJ2gHhzUe4R06J5rfalVwIErNA4>

Data used to run RxGaming on the case studies will happily be made available upon request.

## Declarations

**Competing interests** The authors have no competing interests to declare that are relevant to the content of this article.

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