

leaf_counting

December 7, 2025

1 Introduction

In this notebook, we present more experiments and results of our proposed method to identify leaves from a tree point cloud obtained by a terrestrial LiDAR scanner. We also summarize our method and discuss some drawbacks.

1.1 Approach Summary

Our method goes through several steps:

1. Keep only the tree half which faces the LiDAR scanner.
2. Cluster the tree into smaller clusters.
3. Use different clustering proposing methods (DBSCAN with different scaling of y-axis and z-axis; RANSAC plane fitting) to find the best clustering which gives the most leaf-like clusters for each smaller cluster. The leaf-like clusters are identified by shape analysis.
4. Compute leaf area for each identified leaf cluster and sum them up to get the total leaf area. The leaves areas are approximated by half the area of the convex hull of the leaf clusters, because we assume the leaves are flat surfaces.
5. Only keep the leaves which have area below 0.15 m^2 to avoid suspiciously large leaves.
6. Visualize the final result and show CT scans along different axes, for qualitative evaluation.
7. Report the total leaf area as our estimation of leaf area of the tree.

```
[1]: %matplotlib ipympl
```

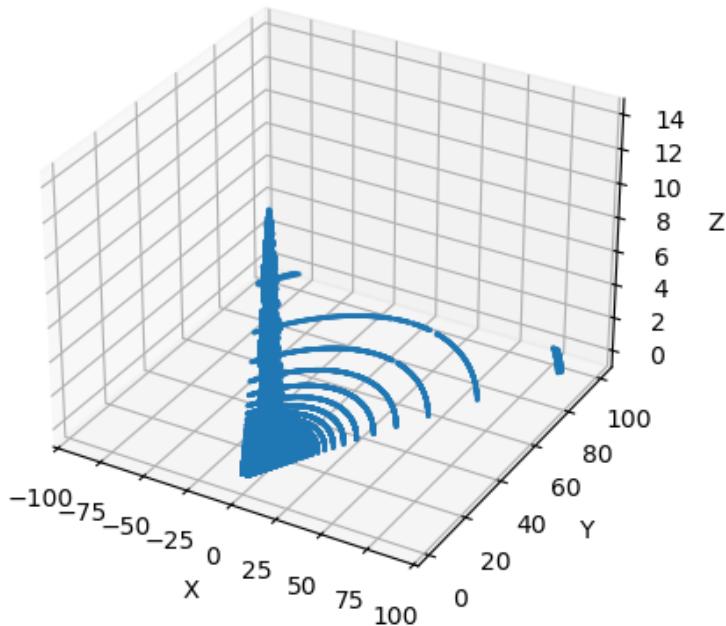
```
import numpy as np
import matplotlib.pyplot as plt
```

```
[2]: # read point clouds data from txt file, each row is a point (x,y,z)
point_clouds = np.loadtxt('tls_points.txt')
print(f"Total points in point cloud: {point_clouds.shape[0]}")
```

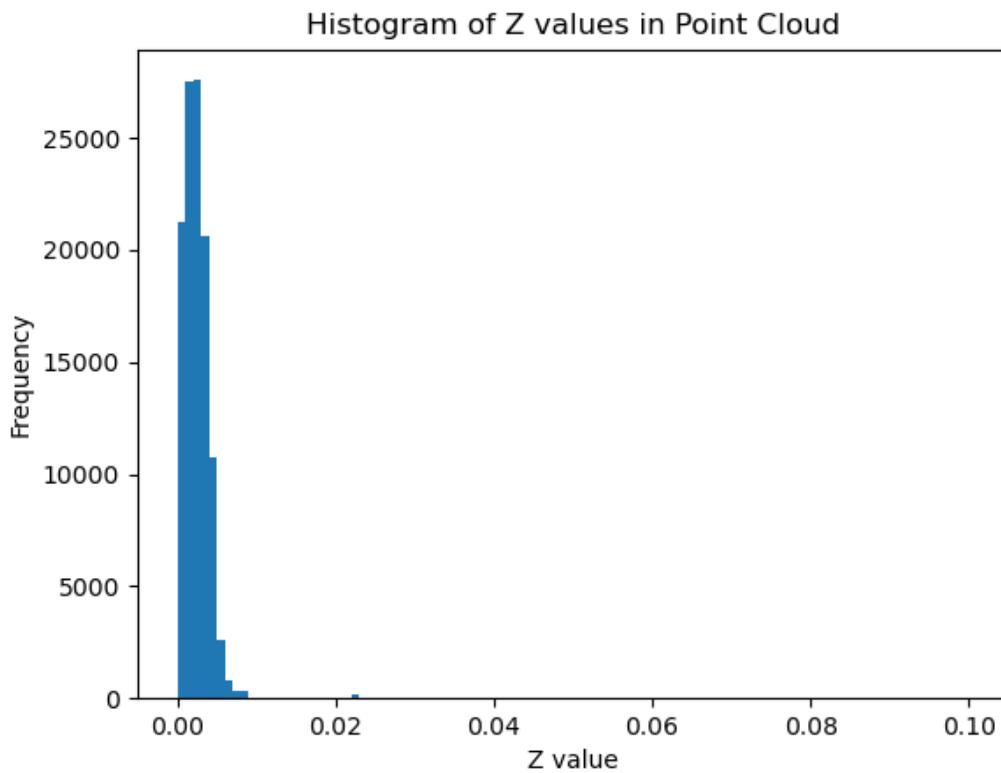
Total points in point cloud: 177748

2 Keep only the tree

```
[3]: # plot the point clouds interactively
fig = plt.figure()
ax = fig.add_subplot(111, projection='3d')
ax.scatter(point_clouds[:,0], point_clouds[:,1], point_clouds[:,2], s=1)
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.show()
```

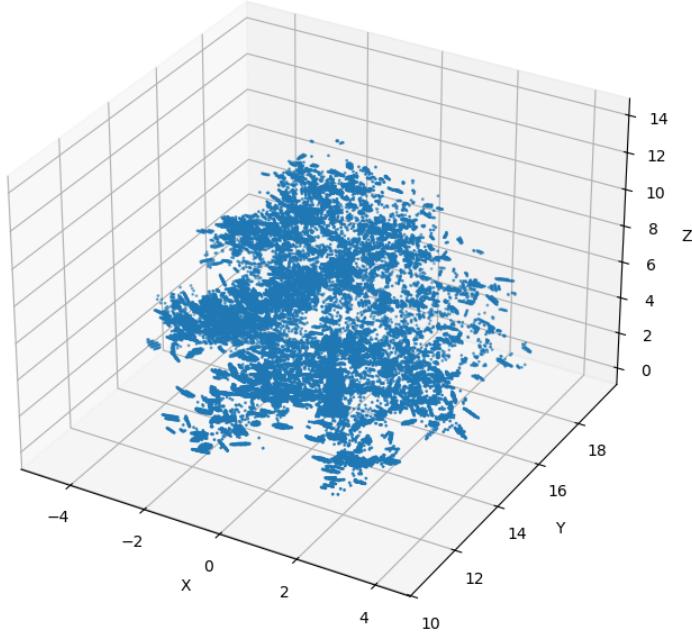


```
[4]: # remove all z points below a certain threshold (e.g., ground level)
# plot histogram of z values to determine threshold
# new plot
fig = plt.figure()
plt.hist(point_clouds[:,2], bins=100, range=(0, 0.1))
plt.xlabel('Z value')
plt.ylabel('Frequency')
plt.title('Histogram of Z values in Point Cloud')
plt.show()
```



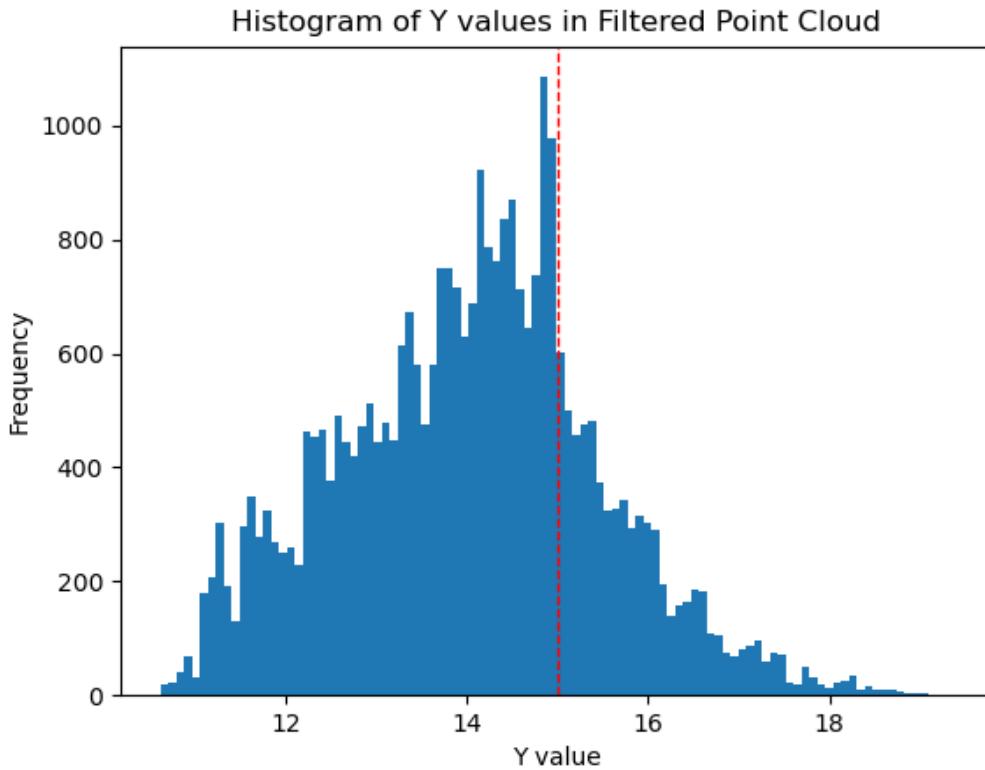
```
[5]: # remove all z_points below 0.02
z_threshold = 0.05
filtered_points = point_clouds[point_clouds[:,2] > z_threshold]
print(f"Points after removing ground level: {filtered_points.shape[0]}")
# plot filtered point clouds
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
ax.scatter(filtered_points[:,0], filtered_points[:,1], filtered_points[:,2], s=1)
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.show()
```

Points after removing ground level: 30960



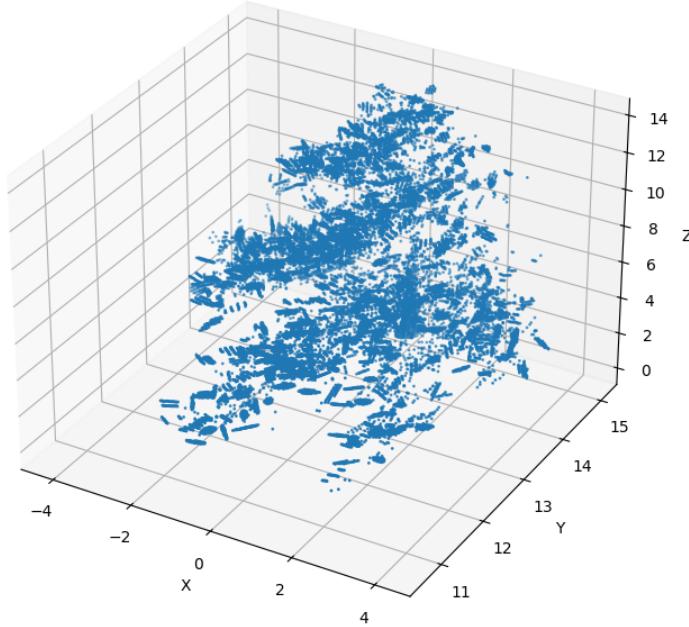
3 Keep only the tree half which faces the LiDAR scanner

```
[6]: # plot histogram on Y values
fig = plt.figure()
plt.hist(filtered_points[:,1], bins=100)
# plot mode
mode_y = 15
plt.axvline(mode_y, color='r', linestyle='dashed', linewidth=1)
plt.xlabel('Y value')
plt.ylabel('Frequency')
plt.title('Histogram of Y values in Filtered Point Cloud')
plt.show()
```



```
[7]: # filter out all points with y > mode_y
y_threshold = mode_y + 0.1 # add some margin in case some leaves get cut off
filtered_points = filtered_points[filtered_points[:,1] < y_threshold]
print(f"Points after removing high Y values: {filtered_points.shape[0]}")
# plot final point clouds
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
ax.scatter(filtered_points[:,0], filtered_points[:,1], filtered_points[:,2], s=1)
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.show()
```

Points after removing high Y values: 24507



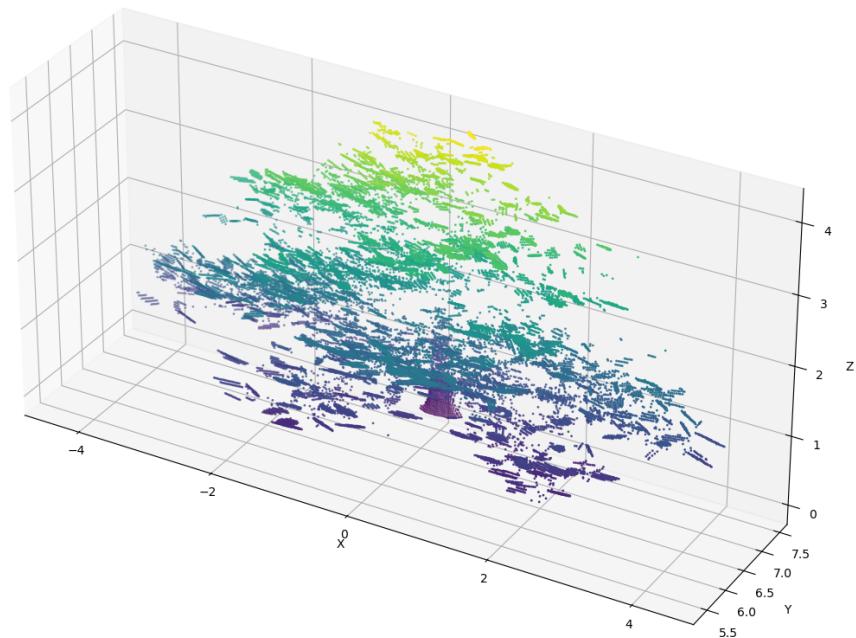
```
[8]: # down sampling the point clouds for faster processing
sample_ratio = 1 # keep 100% of points
num_points = filtered_points.shape[0]
sampled_indices = np.random.choice(num_points, size=int(num_points * sample_ratio), replace=False)
sampled_points = filtered_points[sampled_indices]

# compress the y values by 0.5 to make the point clouds denser in y direction
sampled_points[:,1] = sampled_points[:,1] * 0.5
# compress the z values by 0.7 to make the point clouds denser in z direction
sampled_points[:,2] = sampled_points[:,2] * 0.3

print(f"Points after down sampling: {sampled_points.shape[0]}")
# plot down sampled point clouds
fig = plt.figure(figsize=(13,13))
ax = fig.add_subplot(111, projection='3d')
# color by z value
sc = ax.scatter(sampled_points[:,0], sampled_points[:,1], sampled_points[:,2], c=sampled_points[:,2], cmap='viridis', s=1)
```

```
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
# make all axes the same scale
ax.set_aspect('equal', adjustable='box')
# plt.colorbar(sc, ax=ax, label='Z value', shrink=0.3)
plt.show()
```

Points after down sampling: 24507



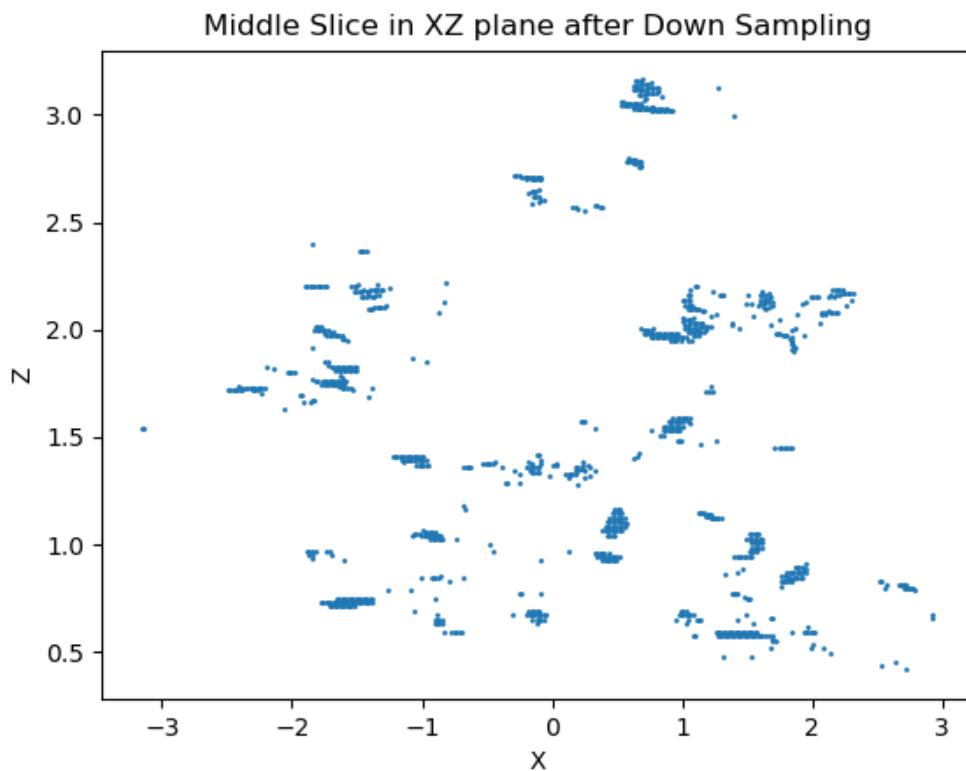
```
[9]: # check a slice in the middle
y_middle = (np.min(sampled_points[:,1]) + np.max(sampled_points[:,1])) / 2
slice_thickness = 0.1
```

```

middle_slice = sampled_points[(sampled_points[:,1] >= y_middle - slice_thickness/2) & (sampled_points[:,1] < y_middle + slice_thickness/2)]
plt.figure()
plt.scatter(middle_slice[:,0], middle_slice[:,2], s=1)
plt.title('Middle Slice in XZ plane after Down Sampling')
plt.xlabel('X')
plt.ylabel('Z')
plt.show()

# the slice looks good, the distance of points between the z and x direction are comparable now.

```



```

[10]: # # show some slices along the x axis
# x_min = np.min(sampled_points[:,0])
# x_max = np.max(sampled_points[:,0])
# slice_thickness = 0.5
# x = x_min
# while x < x_max:
#     slice_points = sampled_points[(sampled_points[:,0] >= x) & (sampled_points[:,0] < x + slice_thickness)]

```

```

#     plt.figure()
#     plt.scatter(slice_points[:,1], slice_points[:,2], s=1)
#     plt.title(f'Slice along X axis from {x:.2f} to {x + slice_thickness:.2f} in YZ plane')
#     plt.xlabel('Y')
#     plt.ylabel('Z')
#     plt.xlim(np.min(sampled_points[:,1]), np.max(sampled_points[:,1]))
#     plt.ylim(np.min(sampled_points[:,2]), np.max(sampled_points[:,2]))
#     plt.show()
#     x += slice_thickness
# # we can see that it does well in some areas, but in some areas, leaves are still merged together or cut into different clusters.
# # this is because

```

4 Finding leaf clusters

We can see that the distance between points are not uniform across the tree. It is affected by: 1. The distance from the LiDAR scanner to the leaf surface. 2. The angle between the leaf surface normal and the direction from the LiDAR scanner to the leaf surface.

DBSCAN requires a fixed distance threshold (eps) to cluster points. Therefore, we will cut the tree into smaller clusters first, then apply DBSCAN on each smaller cluster with an appropriate eps value.

4.1 Clustering the tree into smaller clusters

```
[11]: # use DBSCAN to create clusters of points (branches and leaves)
from sklearn.cluster import DBSCAN

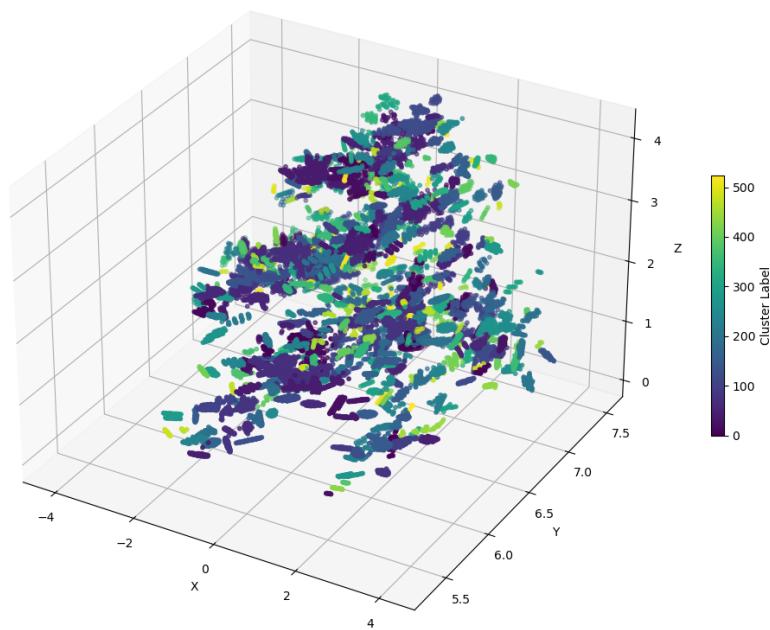
# initial cluster
y_scale = 1
scaled_points = sampled_points.copy()
scaled_points[:,1] = scaled_points[:,1] * y_scale
eps = 0.07
dbscan = DBSCAN(eps=eps, min_samples=5, n_jobs=14)
labels = dbscan.fit_predict(scaled_points)
num_clusters = len(set(labels)) - (1 if -1 in labels else 0)

# plot clusters with different colors
fig = plt.figure(figsize=(13,13))
ax = fig.add_subplot(111, projection='3d')
# remove points which belong to no cluster (label = -1)
valid_indices = labels != -1
sampled_points_plot = scaled_points[valid_indices]
labels_plot = labels[valid_indices]
sc = ax.scatter(sampled_points_plot[:,0], sampled_points_plot[:,1], sampled_points_plot[:,2], c=labels_plot, cmap='viridis', s=10)
```

```

ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.colorbar(sc, ax=ax, label='Cluster Label', shrink=0.3)
plt.show()

```



5 Some initial clustering inspection

```

[12]: # plot ct scan long the y axis and also add cluster ids
y_slices = np.arange(np.min(scaled_points[:,1]), np.max(scaled_points[:,1]), 0.
                     ↵2)
for y_slice in y_slices:

```

```

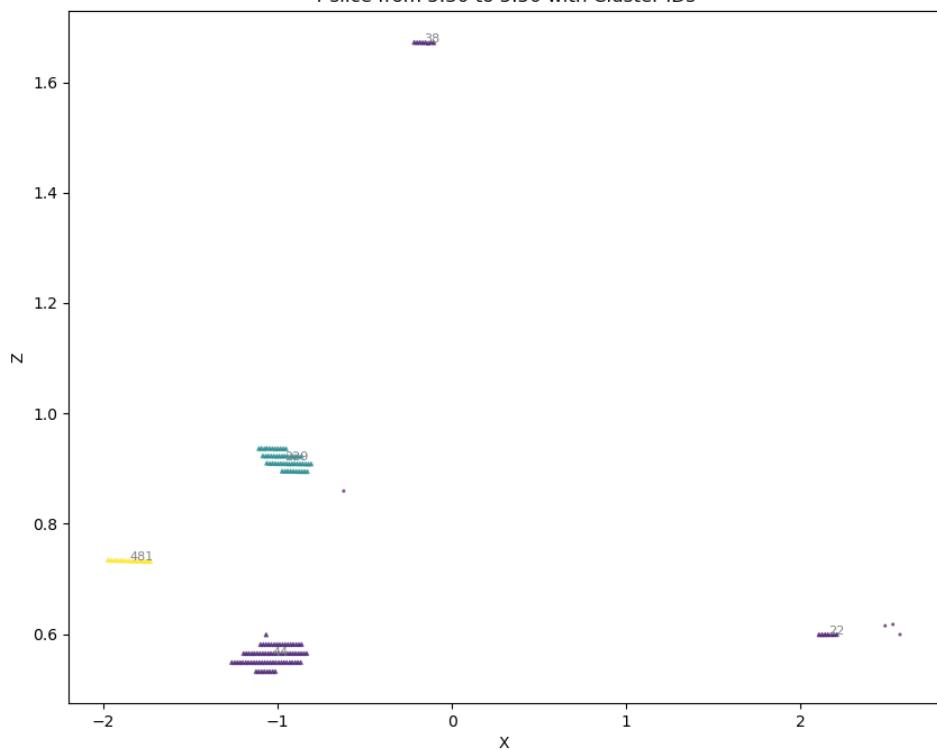
slice_points = scaled_points[(scaled_points[:,1] >= y_slice) &
                             (scaled_points[:,1] < y_slice + 0.2)]
slice_labels = labels[(scaled_points[:,1] >= y_slice) & (scaled_points[:,1] <
y_slice + 0.2)]

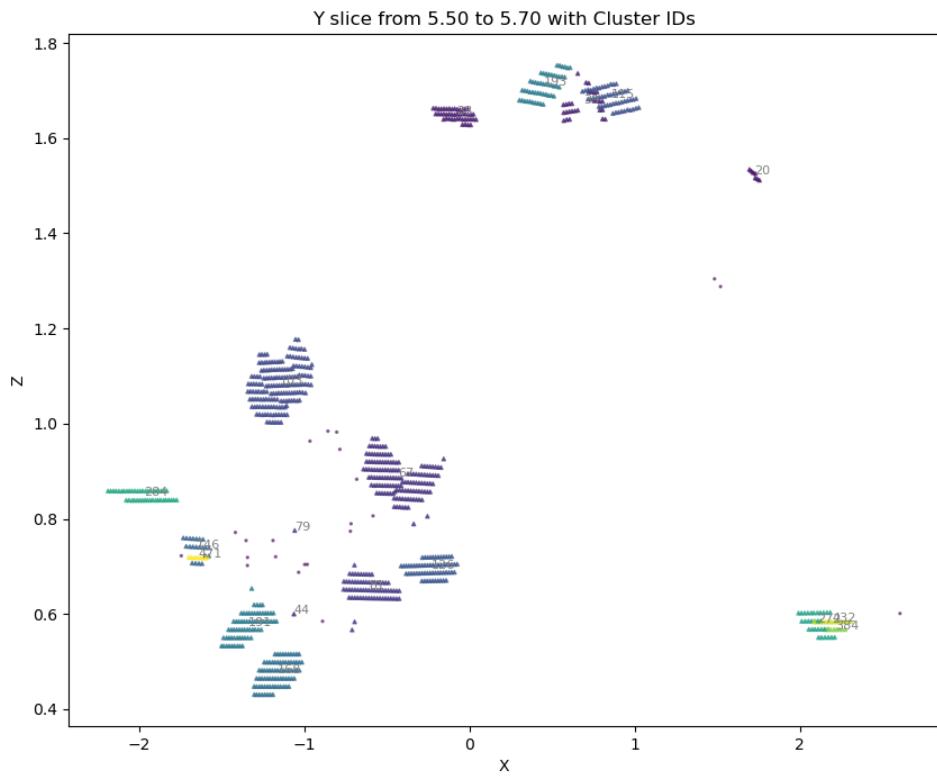
fig, ax = plt.subplots(figsize=(10, 8))

slice_points_plot = slice_points[:, [0, 2]] # plot x and z coordinates
slice_labels_plot = slice_labels
# remove leaf points with area > threshold
leaf_indices = slice_labels_plot != -1
non_leaf_indices = ~leaf_indices
colors_plot = np.array([plt.cm.viridis(label / np.max(slice_labels_plot)) for label in slice_labels_plot])
ax.scatter(slice_points_plot[non_leaf_indices,0], slice_points_plot[non_leaf_indices,1], c=colors_plot[non_leaf_indices], s=2, alpha=0.5)
ax.scatter(slice_points_plot[leaf_indices,0], slice_points_plot[leaf_indices,1], c=colors_plot[leaf_indices], s=5, marker='^', alpha=0.7)
# show cluster ids
for label in set(slice_labels_plot):
    if label == -1:
        continue
    label_indices = slice_labels_plot == label
    if np.sum(label_indices) == 0:
        continue
    mean_x = np.mean(slice_points_plot[label_indices,0])
    mean_z = np.mean(slice_points_plot[label_indices,1])
    ax.text(mean_x, mean_z, str(label), color='gray', fontsize=8, alpha=1)
ax.set_xlabel('X')
ax.set_ylabel('Z')
plt.title(f'Y slice from {y_slice:.2f} to {y_slice + 0.2:.2f} with Cluster IDs')
plt.show()

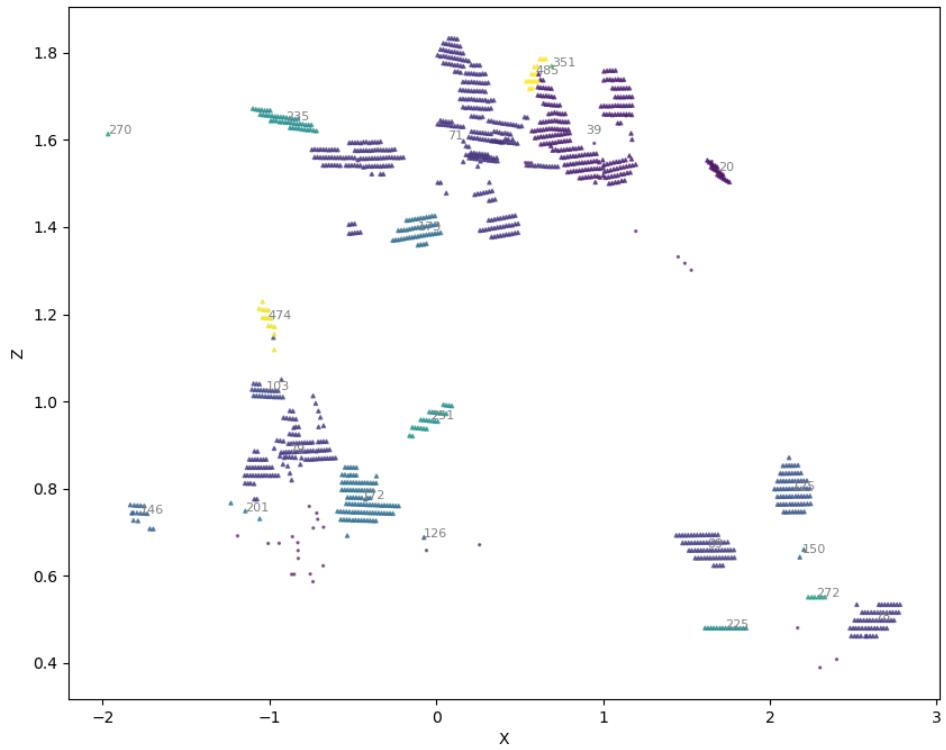
```

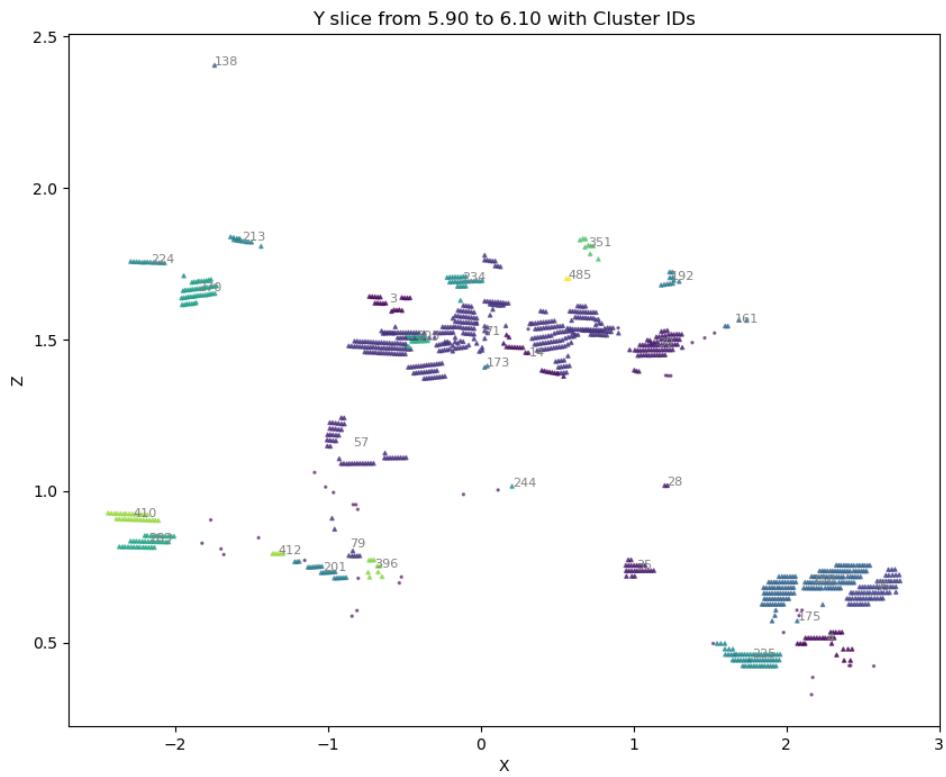
Y slice from 5.30 to 5.50 with Cluster IDs



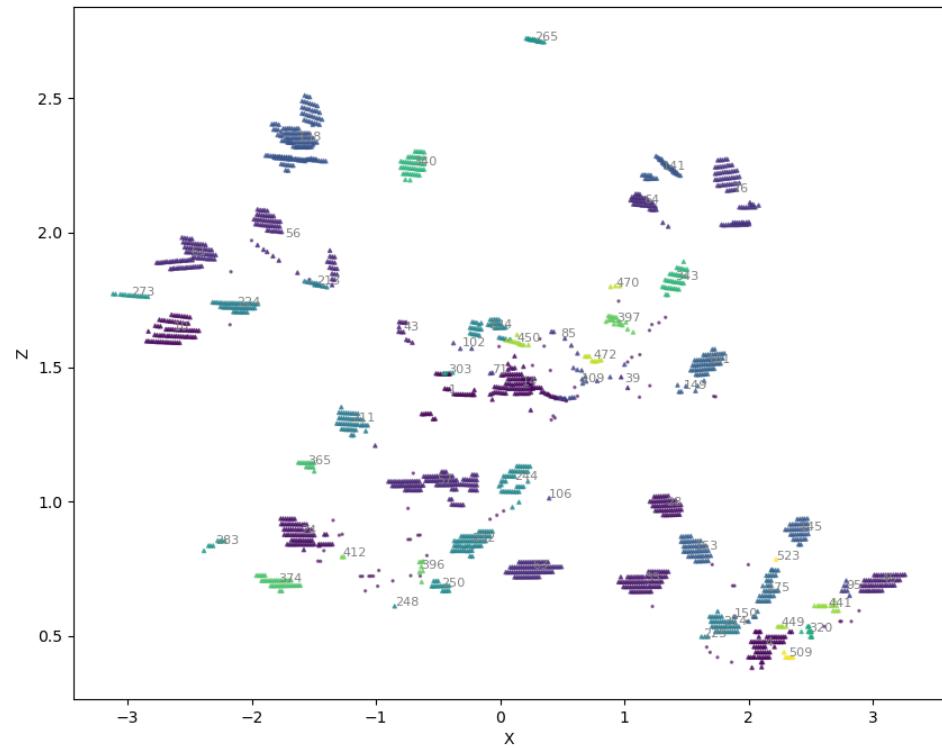


Y slice from 5.70 to 5.90 with Cluster IDs

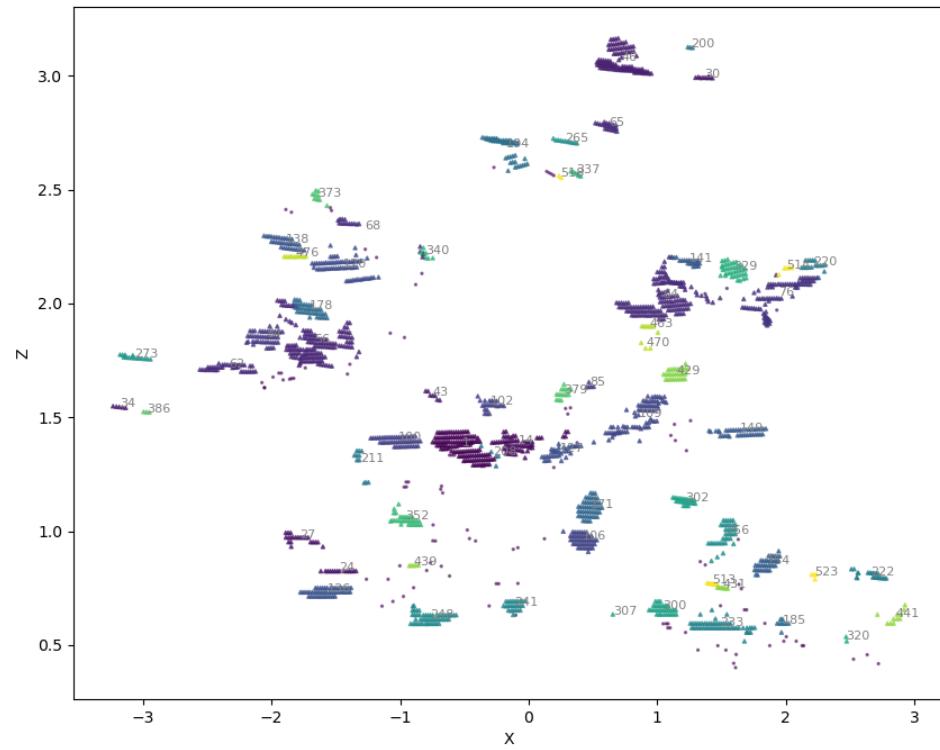




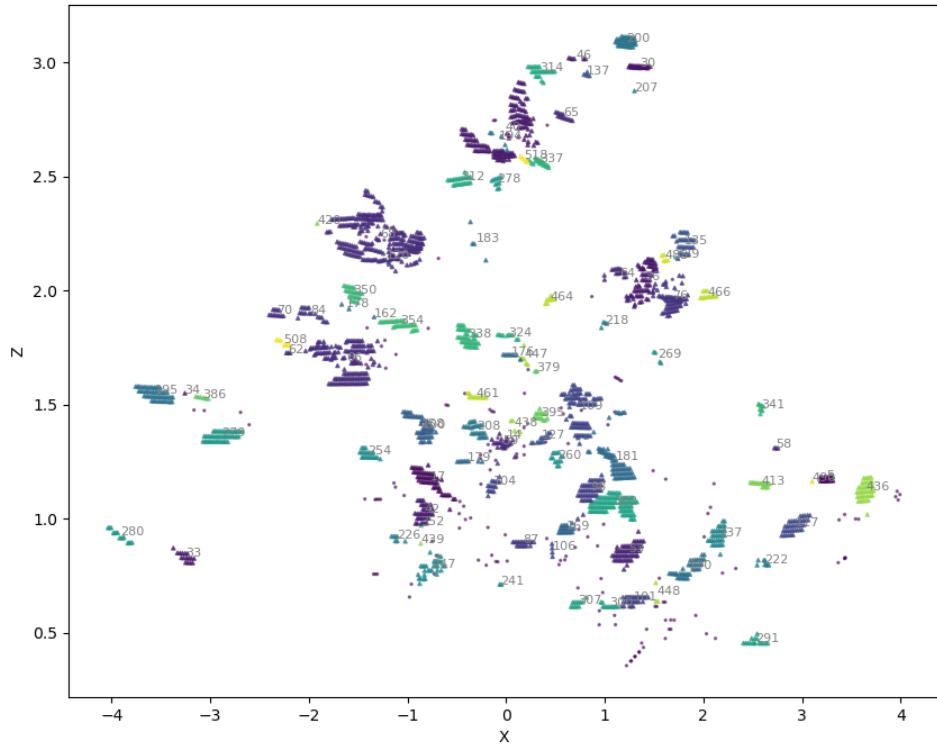
Y slice from 6.10 to 6.30 with Cluster IDs

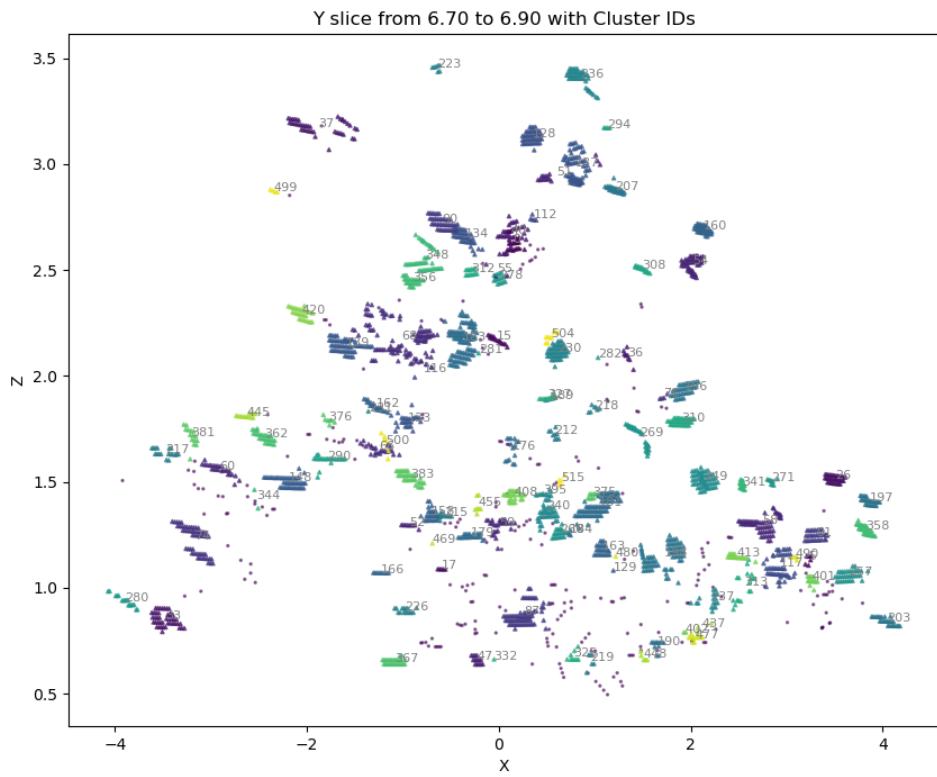


Y slice from 6.30 to 6.50 with Cluster IDs

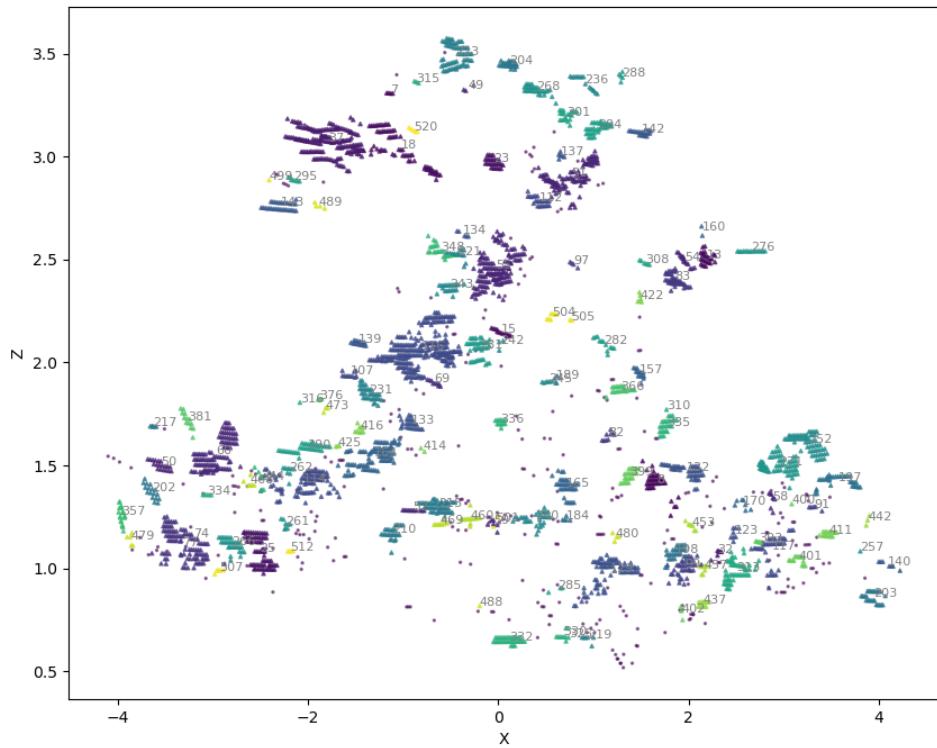


Y slice from 6.50 to 6.70 with Cluster IDs

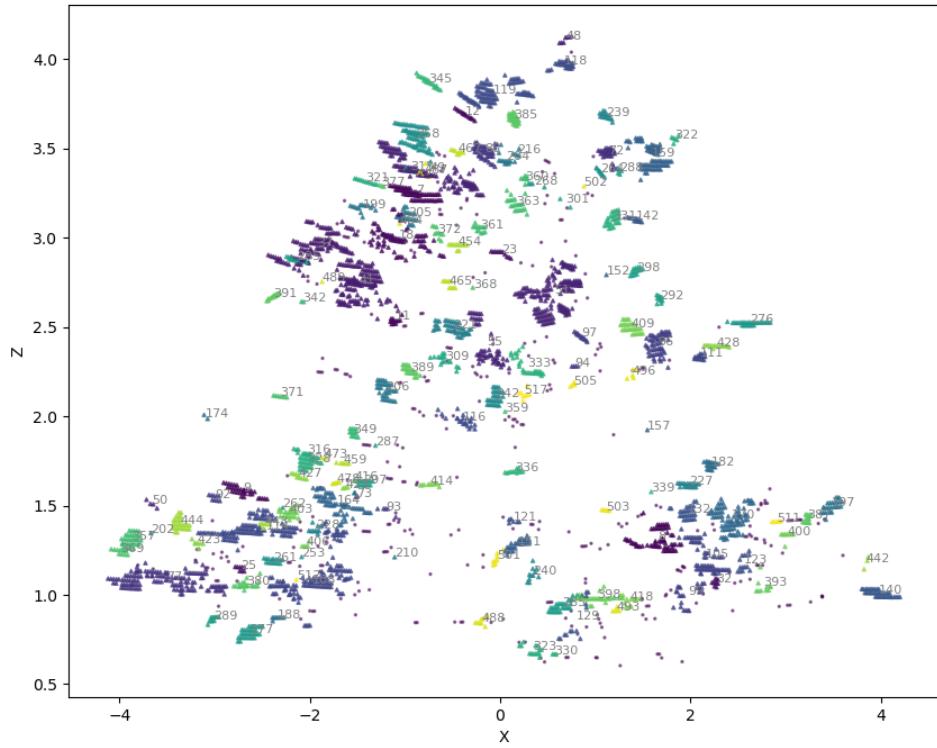


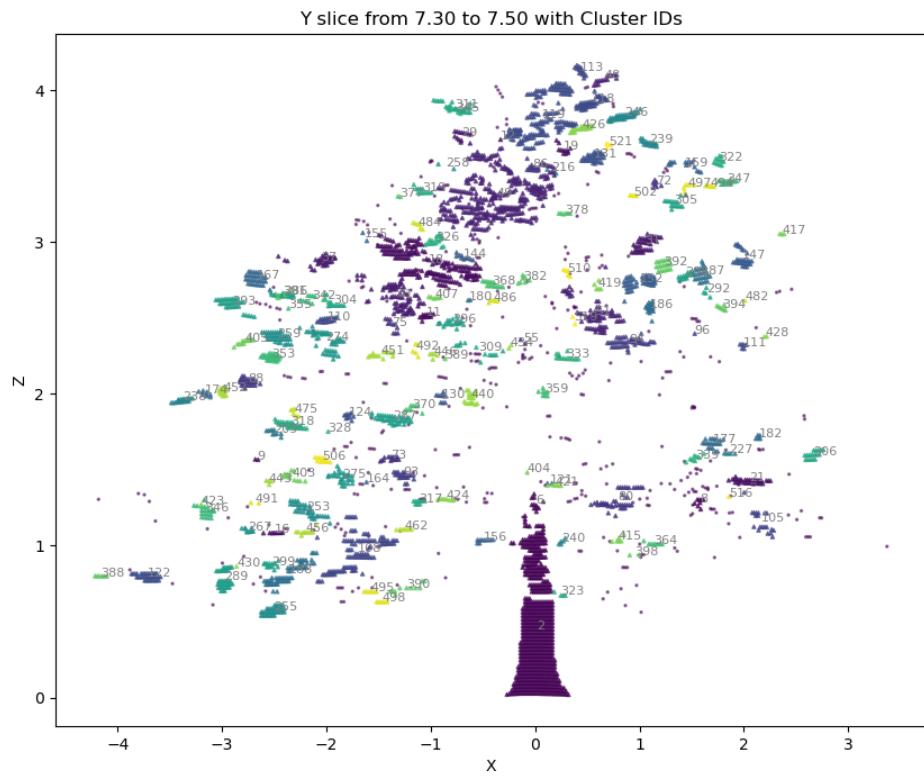


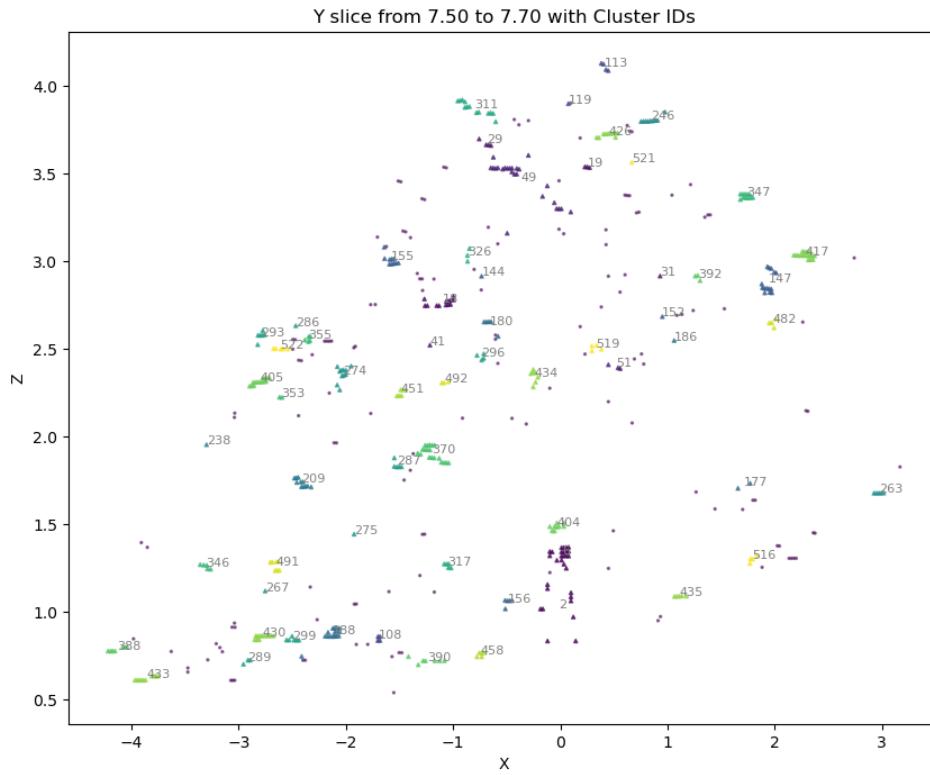
Y slice from 6.90 to 7.10 with Cluster IDs



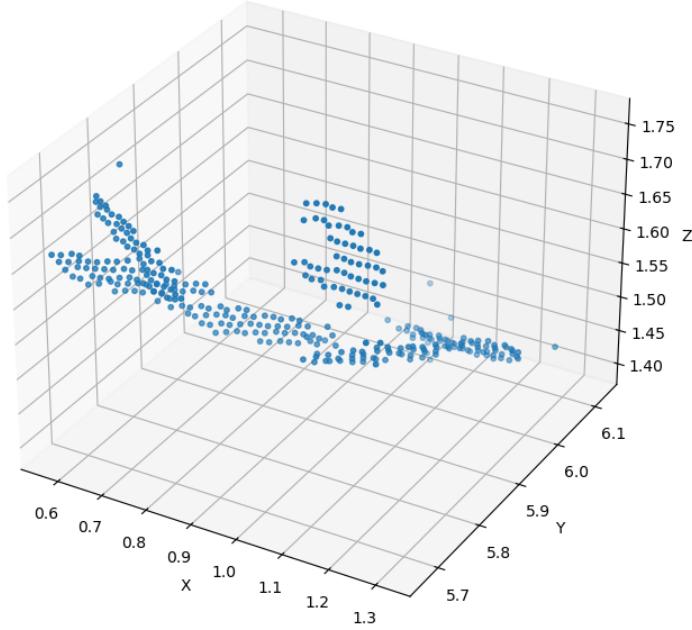
Y slice from 7.10 to 7.30 with Cluster IDs







```
[45]: # inspect a specific cluster
cluster_id_to_inspect = 39
cluster_points = sampled_points[labels == cluster_id_to_inspect]
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
ax.scatter(cluster_points[:,0], cluster_points[:,1], cluster_points[:,2], s=10)
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.show()
```



5.1 For each smaller cluster, find leaf clusters using DBSCAN, RANSAC and shape analysis

```
[14]: # for each large cluster, find the best y_scale, z_scale to maximize the number
      ↴ of leaf-like clusters

from sklearn.decomposition import PCA
from sklearn.linear_model import RANSACRegressor, LinearRegression

# analyze the shape of clusters, we want the shape that characterize leaves best
def analyze_cluster_shape(points):
    """Analyze the shape of a cluster of points using PCA."""
    if points.shape[0] < 3:
        return 0.0, 0.0, 0.0 # not enough points to analyze shape

    # get linearality, planarity, sphericity
    pca = PCA(n_components=3)
    pca.fit(points)
    eigenvalues = pca.explained_variance_
```

```

total_variance = np.sum(eigenvalues)
linearity = (eigenvalues[0] - eigenvalues[1]) / total_variance
planarity = (eigenvalues[1] - eigenvalues[2]) / total_variance
sphericity = eigenvalues[2] / total_variance
return linearity, planarity, sphericity

# leaf-like clusters are defined as clusters with size between certain sizes, ↵
# and planarity > linearity and sphericity
def cluster_is_leaf_like(cluster_points, min_points=10, max_points=80, ↵
    min_ratio=20, plane_threshold=0.02):
    """
        Determine if a cluster of points is leaf-like based on size and shape ↵
        criteria.
    """
    def points_lie_in_a_plane_criteria(points, threshold=0.02):
        # fit a 3D line to the points using linear regression
        lm = LinearRegression()
        lm.fit(points[:, :2], points[:, 2])
        # all point should be within a certain distance to the line, threshold ↵
        = 0.02
        predicted_z = lm.predict(points[:, :2])
        distances = np.abs(points[:, 2] - predicted_z)
        if np.all(distances < threshold):
            return True
        return False

    linearity, planarity, sphericity = analyze_cluster_shape(cluster_points)
    ratio = planarity / (sphericity + 1e-7)
    is_on_plane = points_lie_in_a_plane_criteria(cluster_points, ↵
        threshold=plane_threshold)
    if cluster_points.shape[0] >= min_points and cluster_points.shape[0] <= ↵
        max_points and ratio >= min_ratio and is_on_plane:
        return True, linearity, planarity, sphericity
    return False, linearity, planarity, sphericity

def score_function(points, labels, min_points=10, max_points=80, min_ratio=20, ↵
    plane_threshold=0.02):
    """
        Receive some clustered points and their labels
        and return a score based on quantity and quality of leaf-like clusters ↵
        found
    """
    leaf_cluster_id_2_stats = {}
    for cluster_label in set(labels):
        if cluster_label == -1:

```

```

        continue # skip noise
    cluster_points = points[labels == cluster_label]
    is_leaf, linearity, planarity, sphericity =
    ↵cluster_is_leaf_like(cluster_points,
    ↵
    ↵min_points=min_points,
    ↵
    ↵max_points=max_points,
    ↵
    ↵min_ratio=min_ratio,
    ↵
    ↵plane_threshold=plane_threshold)
    if is_leaf:
        leaf_cluster_id_2_stats[cluster_label] = (linearity, planarity, sphericity)

# score is planarity * number of points in each leaf-like cluster
score = 0
for cluster_label, stats in leaf_cluster_id_2_stats.items():
    planarity = stats[1]
    num_points = np.sum(labels == cluster_label)
    # score += num_points**2 * planarity
    score += num_points**2
return score, leaf_cluster_id_2_stats

def DBSCAN_cluster_optimization(cluster_points, min_points=15, max_points=80, ↵
    ↵min_ratio=10,
                                y_scale_min=0.5, y_scale_max=2.5, ↵
    ↵y_scale_step=0.2,
                                z_scale_min=0.5, z_scale_max=2.5, ↵
    ↵z_scale_step=0.2, plane_threshold=0.02):
    """
        Receive some clustered points and try different DBSCAN parameters to
    ↵find the best clustering
        that maximizes the score_function.

    returns: best_score, best_num_leaf_clusters, clustering_assignment, ↵
    ↵leaf_label_set

    clustering_assignment: array of cluster labels for each point in
    ↵cluster_points
    leaf_label_set: set of cluster labels that are considered leaf-like
    best_score: highest score achieved
    best_num_leaf_clusters: number of leaf-like clusters found at best score
    """

```

```

# try different y_scale and z_scale to scale the cluster points using DBSCAN to find subclusters
# score the subclusters based on the number of leaf-like clusters found
best_score = -1
best_num_leaf_clusters = 0
clustering_assignment = np.zeros(cluster_points.shape[0], dtype=int)
leaf_label_set = set()

list_eps = np.arange(0.1, 0.01, -0.005)

for eps in list_eps:

    scaled_points = cluster_points.copy()
    dbscan = DBSCAN(eps=eps, min_samples=5, n_jobs=16)
    labels = dbscan.fit_predict(scaled_points)

    # # the number of points in -1 cluster should be less than 20% of total points
    num_noise_points = np.sum(labels == -1)
    if num_noise_points > 0.2 * scaled_points.shape[0]:
        continue # skip this scale

    # use ransac to remove points that are not on planes?
    # for each cluster, fit a plane using ransac, keep only inlier points
    for label in set(labels):
        if label == -1: # don't process noise
            continue
        cluster_points_ransac = scaled_points[labels == label]
        if cluster_points_ransac.shape[0] < 3:
            continue
        ransac = RANSACRegressor(residual_threshold=plane_threshold,
                                min_samples=3, max_trials=300)
        X = cluster_points_ransac[:, :2] # use x and y as input
        y = cluster_points_ransac[:, 2] # use z as output
        ransac.fit(X, y)

        inlier_mask = ransac.inlier_mask_
        cluster_points_ransac = cluster_points_ransac[inlier_mask]
        # update labels
        labels_indices = np.where(labels == label)[0]
        for i, idx in enumerate(labels_indices):
            if not inlier_mask[i]:
                # remove outlier point
                labels[idx] = -1 # mark as noise

    # check noise again

```

```

# # the number of points in -1 cluster should be less than 20% of total
points
    num_noise_points = np.sum(labels == -1)
    if num_noise_points > 0.3 * scaled_points.shape[0]:
        continue # skip this scale

    score, leaf_cluster_id_2_stats = score_function(scaled_points, labels,
min_points=min_points,
                                                max_points=max_points,
min_ratio=min_ratio, plane_threshold=plane_threshold)

    if score > best_score or (np.abs(score - best_score) <= 5 and
len(leaf_cluster_id_2_stats) > best_num_leaf_clusters):
        # if len(leaf_cluster_id_2_stats) > best_num_leaf_clusters or (score >
best_score and len(leaf_cluster_id_2_stats) == best_num_leaf_clusters):
            best_score = score
            best_num_leaf_clusters = len(leaf_cluster_id_2_stats)
            leaf_label_set = set(leaf_cluster_id_2_stats.keys())
            # outlier points are labeled as -1
            clustering_assignment = labels.copy()

    return best_score, best_num_leaf_clusters, clustering_assignment,
leaf_label_set

# implementing sequential RANSAC to find 2d leaf planes in 3d point clouds
def find_leaf_planes_ransac(cluster_points, distance_threshold=0.01,
min_inliers=20, dbscan_min_points=15, dbscan_max_points=80,
dbscan_min_ratio=10):
    remaining_points = cluster_points.copy()
    leaf_planes = []

    list_len_remaining = []
    while remaining_points.shape[0] >= min_inliers:
        # fit RANSAC plane model
        ransac = RANSACRegressor(residual_threshold=distance_threshold,
min_samples=3, max_trials=300)
        X = remaining_points[:, :2] # use x and y as input
        y = remaining_points[:, 2] # use z as output
        ransac.fit(X, y)

        inlier_mask = ransac.inlier_mask_
        inlier_points = remaining_points[inlier_mask]

        # there can be multiple cluster in inlier points so we want to separate
them

```

```

# use DBSCAN to separate them, find the best DBSCAN clustering and
# remove good clusters.
    best_score, best_num_leaf_clusters, clustering_assignment,
    ↵leaf_label_set = DBSCAN_cluster_optimization(inlier_points,
    ↵
    ↵            min_points=dbscan_min_points,
    ↵
    ↵            max_points=dbscan_max_points,
    ↵
    ↵            min_ratio=dbscan_min_ratio)

    # # set inlier_points to only those points that are labeled as
    ↵leaf-like clusters
        for cluster_id in leaf_label_set:
            cluster_points = inlier_points[clustering_assignment == cluster_id]
            # if cluster_points.shape[0] >= min_inliers:
            leaf_planes.append(cluster_points)

            new_inlier_mask = list()
            inlier_points_pos = 0
            for i in range(inlier_mask.shape[0]):
                if inlier_mask[i]:
                    if clustering_assignment[inlier_points_pos] in leaf_label_set:
                        new_inlier_mask.append(True)
                    else:
                        new_inlier_mask.append(False)
                    inlier_points_pos += 1
                else:
                    new_inlier_mask.append(False)

            # remove inliers from remaining points
            outlier_mask = np.logical_not(new_inlier_mask)
            remaining_points = remaining_points[outlier_mask]

            len_remaining = remaining_points.shape[0]
            list_len_remaining.append(len_remaining)
            # if 3 time and still no change, break
            if len(list_len_remaining) >= 5:
                if all(x == list_len_remaining[-1] for x in list_len_remaining[-3:-1]):
                    break

        return leaf_planes

param_1 = {

```

```

# use with optimal number of leaf-like clusters objective
'dbscan':{
    'min_points':12,
    'max_points':70,
    'min_ratio':20,
    'plane_threshold':0.04,
},
'randsac':{
    'distance_threshold':0.04,
    'min_inliers':12,
    'dbscan_min_points':12,
    'dbscan_max_points':70,
    'dbscan_min_ratio':20
}
} # very good cluster, ~430 clusters, but failed to split some leaves

param_2 = {
    # use with optimal number of leaf-like clusters objective
    'dbscan':{
        'min_points':15,
        'max_points':80,
        'min_ratio':20,
        'plane_threshold':0.015
    },
    'randsac':{
        'distance_threshold':0.03,
        'min_inliers':15,
        'dbscan_min_points':12,
        'dbscan_max_points':80,
        'dbscan_min_ratio':20
    }
}
param = param_1

def optimize_scales_for_cluster(cluster_points, ransac_only=False):
    """
    This function should return the best subclustering labels for the given
    cluster points
    1. Try different y_scale and z_scale to scale the cluster points using
    DBSCAN to find subclusters
    2. Score the subclusters based on the number of leaf-like clusters found
    3. If number of leaf-like clusters is 0, try sequential RANSAC to find leaf
    planes
    4. Return the best clustering assignment.
    """
    # try DBSCAN first

```

```

best_score = -1
clustering_assignment = -1 * np.ones(cluster_points.shape[0], dtype=int)
leaf_label_set = set()
best_num_leaf_clusters = 0
if not ransac_only:
    best_score, best_num_leaf_clusters, clustering_assignment,
    ↪ leaf_label_set = DBSCAN_cluster_optimization(cluster_points,
    ↪ min_points=param['dbscan']['min_points'],
    ↪ max_points=param['dbscan']['max_points'],
    ↪ min_ratio=param['dbscan']['min_ratio'],
    ↪ plane_threshold=param['dbscan']['plane_threshold']))
dbscan_best_score = 0
for label in leaf_label_set:
    num_points = np.sum(clustering_assignment == label)
    dbscan_best_score += num_points**2
best_score = dbscan_best_score

# # Try RANSAC
best_leaf_planes = []
scaled_points = cluster_points.copy()
leaf_planes = find_leaf_planes_ransac(scaled_points,
    ↪ distance_threshold=param['ransac']['distance_threshold'],
    ↪ min_inliers=param['ransac']['min_inliers'],
    ↪ dbscan_min_points=param['ransac']['dbscan_min_points'],
    ↪ dbscan_max_points=param['ransac']['dbscan_max_points'],
    ↪ dbscan_min_ratio=param['ransac']['dbscan_min_ratio'])
# score is total number of points in leaf planes
score = sum(plane.shape[0]**2 for plane in leaf_planes)

if score > best_score or (np.abs(score - best_score) <= 5 and
    ↪ len(leaf_planes) > best_num_leaf_clusters):
    # if len(leaf_planes) > best_num_leaf_clusters or (score > best_score and
    ↪ len(leaf_planes) == best_num_leaf_clusters):
        best_score = score
        best_num_leaf_clusters = len(leaf_planes)
        best_leaf_planes = leaf_planes

# translate best_leaf_planes to clustering_assignment

```

```

    if len(best_leaf_planes) > 0:
        clustering_assignment = -1 * np.ones(cluster_points.shape[0], dtype=int)
        cluster_id = 0
        leaf_label_set = set()
        for plane in best_leaf_planes:
            for point in plane:
                # find index of point in cluster_points
                indices = np.where((np.round(cluster_points, decimals=4) == np.round(point, decimals=4)).all(axis=1))[0]
                assert len(indices) > 0, "Point from leaf plane not found in original cluster points"
                for index in indices:
                    clustering_assignment[index] = cluster_id
                    leaf_label_set.add(cluster_id)
                    cluster_id += 1
        print(f"After RANSAC: Best Score: {best_score}, Best Number of leaf-like clusters: {best_num_leaf_clusters}")
    else:
        print(f"After DBSCAN: Best Score: {best_score}, Best Number of leaf-like clusters: {best_num_leaf_clusters}")

    return best_score, best_num_leaf_clusters, clustering_assignment, leaf_label_set

```

[51]: # try dbscan optimization the specific cluster

```

cluster_id_to_inspect = 39
cluster_points = sampled_points[labels == cluster_id_to_inspect]
best_score, best_num_leaf_clusters, clustering_assignment, leaf_label_set = DBSCAN_cluster_optimization(cluster_points, plane_threshold=0.05, max_points=80)

```

[52]: # plot cluster 14 with leaf-like clusters highlighted

```

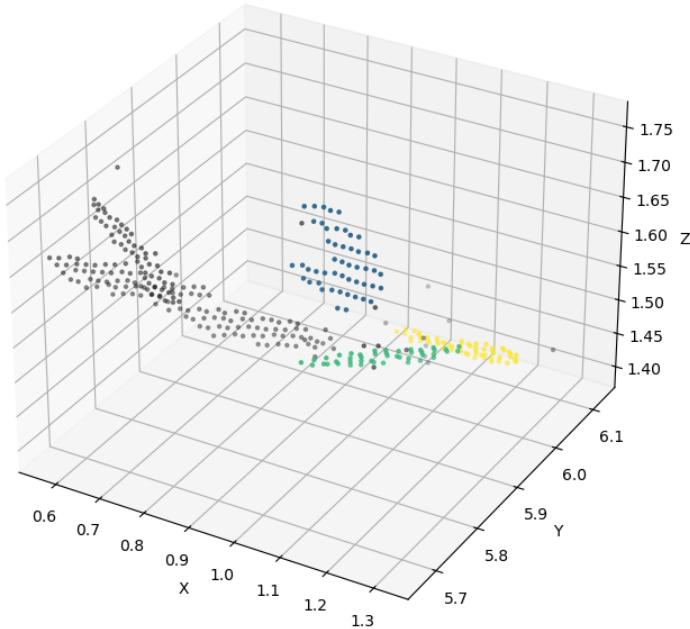
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
# for each cluster in leaf_label_set map cluster id to a color
colors = []
for i in range(clustering_assignment.shape[0]):
    if clustering_assignment[i] in leaf_label_set:
        colors.append(plt.cm.viridis(clustering_assignment[i] / np.max(list(leaf_label_set))))
    else:
        colors.append((0,0,0, 0.5)) # light gray for non-leaf clusters
colors = np.array(colors)
ax.scatter(cluster_points[:,0], cluster_points[:,1], cluster_points[:,2], c=colors, s=5)

```

```

ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.show()

```



```

[48]: best_score_ransac, best_num_leaf_clusters_ransac, clustering_assignment_ransac,_
        ↪leaf_label_set_ransac = optimize_scales_for_cluster(
            cluster_points, ransac_only=True)

# plot ransac cluster 14 with leaf-like clusters highlighted
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
# for each cluster in leaf_label_set map cluster id to a color
colors_ransac = []
for i in range(clustering_assignment_ransac.shape[0]):
    if clustering_assignment_ransac[i] in leaf_label_set_ransac:
        colors_ransac.append(plt.cm.viridis(clustering_assignment_ransac[i] /_
        ↪np.max(list(leaf_label_set_ransac))))
    else:

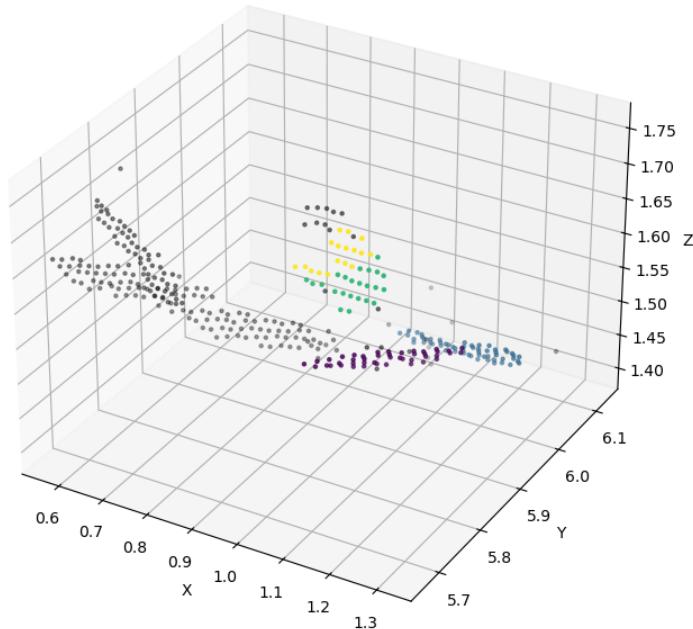
```

```

    colors_ransac.append((0,0,0, 0.5)) # light gray for non-leaf clusters
colors_ransac = np.array(colors_ransac)
ax.scatter(cluster_points[:,0], cluster_points[:,1], cluster_points[:,2], c=colors_ransac, s=5)
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.show()

```

After RANSAC: Best Score: 5890, Best Number of leaf-like clusters: 4



[18]: cluster_id_2_best_scales = {}

[19]: # for cluster_label in set(labels):
if cluster_label in cluster_id_2_best_scales:
continue # already processed

if cluster_label == -1:
continue # skip noise

```

#     cluster_points = scaled_points[labels == cluster_label]

#     best_score, best_num_leaf_clusters, best_clustering, is_leaf_label = ↵
#         optimize_scales_for_cluster(cluster_points)
#     print(f"Cluster {cluster_label}: Best Score (leaf-like clusters): {best_score}, Number of leaf-like clusters: {best_num_leaf_clusters}")
#     cluster_id_2_best_scales[cluster_label] = (best_score, ↵
#         best_num_leaf_clusters, best_clustering, is_leaf_label)

# rewrite this loop to be parallel
from joblib import Parallel, delayed
def process_cluster(cluster_label, scaled_points, labels):
    if cluster_label == -1:
        return cluster_label, None # skip noise
    cluster_points = scaled_points[labels == cluster_label]

    best_score, best_num_leaf_clusters, clustering_assignment, leaf_label_set = ↵
    optimize_scales_for_cluster(cluster_points)
    # print(f"Cluster {cluster_label}: Best Score (leaf-like clusters): {best_score}, Number of leaf-like clusters: {best_num_leaf_clusters}")
    return cluster_label, (best_score, best_num_leaf_clusters, ↵
        clustering_assignment, leaf_label_set)
results = Parallel(n_jobs=16)(delayed(process_cluster)(cluster_label, ↵
    scaled_points, labels) for cluster_label in set(labels))
cluster_id_2_best_scales = {cluster_label: result for cluster_label, result in ↵
    results if result is not None}

```

After DBSCAN: Best Score: 361, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 784, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 225, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 324, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 361, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 576, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 4900, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 729, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 2084, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 729, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1744, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 841, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1521, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1296, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 5340, Best Number of leaf-like clusters: 4
After DBSCAN: Best Score: 441, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0

After RANSAC: Best Score: 3445, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 4570, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 529, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2916, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 2589, Best Number of leaf-like clusters: 3
After RANSAC: Best Score: 196, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 1024, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 169, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2916, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1928, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 4761, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 256, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 900, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3025, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1865, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 196, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 529, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 400, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 10654, Best Number of leaf-like clusters: 5
After RANSAC: Best Score: 5450, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 3136, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2379, Best Number of leaf-like clusters: 3
After RANSAC: Best Score: 2176, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 400, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1849, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 7376, Best Number of leaf-like clusters: 3
After RANSAC: Best Score: 1845, Best Number of leaf-like clusters: 3
After RANSAC: Best Score: 1441, Best Number of leaf-like clusters: 3
After RANSAC: Best Score: 4874, Best Number of leaf-like clusters: 4
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 576, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 3972, Best Number of leaf-like clusters: 7
After DBSCAN: Best Score: 1764, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1296, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 9960, Best Number of leaf-like clusters: 4
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 8425, Best Number of leaf-like clusters: 12
After DBSCAN: Best Score: 4900, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2669, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 144, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 144, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 961, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0

After DBSCAN: Best Score: 3969, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3364, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 4489, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 4917, Best Number of leaf-like clusters: 13
After RANSAC: Best Score: 820, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 841, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 8855, Best Number of leaf-like clusters: 6
After DBSCAN: Best Score: 1450, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 676, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 6922, Best Number of leaf-like clusters: 3
After RANSAC: Best Score: 7652, Best Number of leaf-like clusters: 5
After DBSCAN: Best Score: 4225, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3249, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1936, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1296, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 729, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 4624, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 4148, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 4633, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 2500, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 2481, Best Number of leaf-like clusters: 8
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 7107, Best Number of leaf-like clusters: 8
After DBSCAN: Best Score: 2601, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 529, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 4141, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 324, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 256, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2809, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1024, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 361, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1445, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 2704, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 6046, Best Number of leaf-like clusters: 7
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 4761, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 196, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 9614, Best Number of leaf-like clusters: 4
After RANSAC: Best Score: 2197, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 1156, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0

After DBSCAN: Best Score: 441, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1571, Best Number of leaf-like clusters: 5
After DBSCAN: Best Score: 4096, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1764, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2025, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1156, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 12191, Best Number of leaf-like clusters: 8
After RANSAC: Best Score: 4710, Best Number of leaf-like clusters: 4
After DBSCAN: Best Score: 1637, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 6482, Best Number of leaf-like clusters: 5
After DBSCAN: Best Score: 2025, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2500, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 2250, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 2401, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2025, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1156, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1924, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 3481, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1089, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 2993, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 961, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1521, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1156, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2025, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1296, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 4356, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 625, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1010, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 1296, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1179, Best Number of leaf-like clusters: 3
After RANSAC: Best Score: 2837, Best Number of leaf-like clusters: 7
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 144, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1280, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 169, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 6915, Best Number of leaf-like clusters: 7
After DBSCAN: Best Score: 1521, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3481, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 3796, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 7789, Best Number of leaf-like clusters: 5
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 625, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 441, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1

After RANSAC: Best Score: 4900, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1652, Best Number of leaf-like clusters: 3
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 5965, Best Number of leaf-like clusters: 4
After RANSAC: Best Score: 484, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 2601, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 3133, Best Number of leaf-like clusters: 3
After DBSCAN: Best Score: 2500, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 1764, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 961, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 5389, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2209, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 4489, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2601, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2916, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1444, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 169, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1849, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1825, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 676, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 514, Best Number of leaf-like clusters: 2
After RANSAC: Best Score: 2986, Best Number of leaf-like clusters: 3
After DBSCAN: Best Score: 324, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1225, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1027, Best Number of leaf-like clusters: 5
After RANSAC: Best Score: 683, Best Number of leaf-like clusters: 3
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 1296, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 1600, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 961, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1156, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 400, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 4201, Best Number of leaf-like clusters: 5
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 625, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2601, Best Number of leaf-like clusters: 1

After DBSCAN: Best Score: 1600, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 625, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 2050, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 4489, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 2487, Best Number of leaf-like clusters: 6
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 729, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 400, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 4900, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3364, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 625, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2809, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2401, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2116, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 400, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1089, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 625, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 400, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 961, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3600, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1764, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2304, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3600, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2401, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 441, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1225, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 676, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 196, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1690, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 3249, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 361, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 841, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 784, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 1681, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 1296, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1800, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 1225, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1156, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1

After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 676, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1213, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 1156, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 900, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2209, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1369, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 841, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 625, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1521, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1849, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 529, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 1089, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2401, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1024, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 784, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1601, Best Number of leaf-like clusters: 3
After DBSCAN: Best Score: 1089, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2116, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1849, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 628, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 961, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 144, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 196, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1296, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 1225, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 400, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 3481, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 2500, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 872, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 729, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 361, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 1764, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 256, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 484, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After RANSAC: Best Score: 730, Best Number of leaf-like clusters: 2
After DBSCAN: Best Score: 196, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 169, Best Number of leaf-like clusters: 1


```

After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0
After DBSCAN: Best Score: 144, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 144, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 144, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 225, Best Number of leaf-like clusters: 1
After RANSAC: Best Score: 144, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 196, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 289, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 256, Best Number of leaf-like clusters: 1
After DBSCAN: Best Score: 0, Best Number of leaf-like clusters: 0

```

```
[20]: # estimate number of leaves
total_num_leaves = 0
for cluster_label, (best_score, best_num_leaf_clusters, clustering_assignment, ↴
    leaf_label_set) in cluster_id_2_best_scales.items():
    total_num_leaves += best_num_leaf_clusters
print(f"Estimated total number of leaves: {total_num_leaves}")
```

Estimated total number of leaves: 546

```
[21]: ## dump cluster_id_2_best_scales to a file
# import pickle
# with open('cluster_id_2_best_scales_v9.pkl', 'wb') as f:
#     pickle.dump(cluster_id_2_best_scales, f)

# # dump all points and their cluster labels to a file
# import pandas as pd
# df = pd.DataFrame(scaled_points, columns=['X', 'Y', 'Z'])
# df['ClusterLabel'] = labels
# df.to_csv('scaled_points_with_clusters_v9.csv', index=False)

# # load cluster_id_2_best_scales from a file
# import pickle
```

```

# with open('cluster_id_2_best_scales_v8.pkl', 'rb') as f:
#     cluster_id_2_best_scales = pickle.load(f)

# # load all points and their cluster labels from a file
# import pandas as pd
# df = pd.read_csv('scaled_points_with_clusters_v8.csv')
# scaled_points = df[['X', 'Y', 'Z']].values
# labels = df['ClusterLabel'].values

```

6 Visualize the final result

```
[22]: # add sub-cluster labels to the main labels
new_labels = -1 * np.ones_like(labels, dtype=int)
is_leaf_label = np.zeros_like(labels, dtype=bool)
cur_unique_label = 0
wood_cluster_id = -1
key_to_new_label = {}
for cluster_label in set(labels):
    if cluster_label == -1:
        continue # skip noise
    cluster_points = scaled_points[labels == cluster_label]
    cluster_points_global_indices = np.where(labels == cluster_label)[0]

    if cluster_label in cluster_id_2_best_scales:
        best_score, best_num_leaf_clusters, sub_clustering_assignment, ↴
        sub_leaf_label_set = cluster_id_2_best_scales[cluster_label]
        if len(sub_leaf_label_set) == 0:
            # print(f"Cluster {cluster_label} has no leaf-like subclusters, ↴
            # assigning new label to whole cluster")
            # for global_index in cluster_points_global_indices:
            #     new_labels[global_index] = wood_cluster_id
            #     is_leaf_label[global_index] = False
            #     continue

        sub_labels = sub_clustering_assignment
        for i, point in enumerate(cluster_points):
            global_index = cluster_points_global_indices[i]
            if sub_labels[i] == -1:
                continue # skip noise
            label_key = "_" .join((str(cluster_label), str(sub_labels[i] + 2)))
            if label_key not in key_to_new_label:
                key_to_new_label[label_key] = cur_unique_label
                cur_unique_label += 1
            new_labels[global_index] = key_to_new_label[label_key]
            is_leaf_label[global_index] = sub_labels[i] in sub_leaf_label_set

```

```

    else:
        print(f"Cluster {cluster_label} has no subclustering info, assigning
↳new label to whole cluster")
        # there should be no such cluster

```

```
[23]: total_sub_leaf_clusters = 0
total_check = 0
for k, v in cluster_id_2_best_scales.items():
    total_sub_leaf_clusters += len(v[3])
    total_check += v[1]
print(f"Total unique clusters: {len(set(new_labels))}, Total sub leaf clusters
↳from all large clusters: {total_sub_leaf_clusters}, Total check:_
↳{total_check}")

# check the new labels
unique_new_labels = set(new_labels)
print(f"Total unique sub-cluster labels: {len(unique_new_labels)}")
for label in unique_new_labels:
    is_leaf = is_leaf_label[new_labels == label]
    # assert is_leaf is either all True or all False
    if not (np.all(is_leaf) or not np.any(is_leaf)):
        print(f"Label {label} has mixed leaf labels: {is_leaf}")

```

Total unique clusters: 748, Total sub leaf clusters from all large clusters:
546, Total check: 546
Total unique sub-cluster labels: 748

```
[24]: # key_to_new_label
```

```
[25]: unique_labels = np.unique(new_labels)
num_unique_labels = len(unique_labels) - (1 if -1 in unique_labels else 0)
# generate a random map between unique labels and colors
label_to_color = {}
for label in unique_labels:
    if label == -1:
        label_to_color[label] = (0, 0, 0) # black for noise
    else:
        label_to_color[label] = np.random.rand(3,)
```

```
[26]: # revert to original scales
orig_points = scaled_points.copy()
orig_points[:,1] = scaled_points[:,1] / 0.5
orig_points[:,2] = scaled_points[:,2] / 0.3
```

```
[27]: # plot tree using new labels
fig = plt.figure(figsize=(12,15))
ax = fig.add_subplot(111, projection='3d')
```

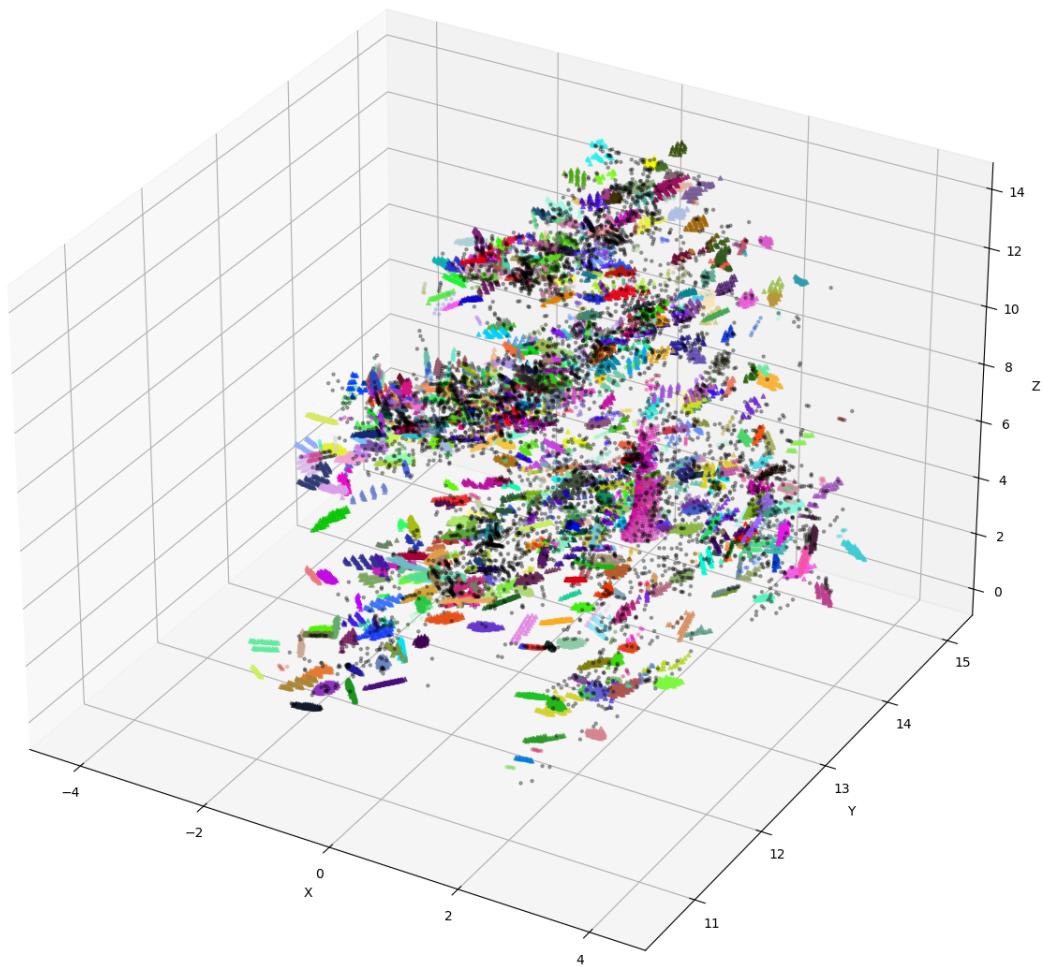
```

# remove points which belong to no cluster (label = -1)
# valid_indices = new_labels != -1
# sampled_points_plot = orig_points[valid_indices]
# labels_plot = new_labels[valid_indices]
# leaf_indices = is_leaf_label[valid_indices]
sampled_points_plot = orig_points
labels_plot = new_labels
leaf_indices = is_leaf_label

colors_plot = np.array([label_to_color[label] for label in labels_plot])
# plot leaf points as triangles

non_leaf_indices = ~leaf_indices
ax.scatter(sampled_points_plot[non_leaf_indices,0], □
    ↪sampled_points_plot[non_leaf_indices,1], □
    ↪sampled_points_plot[non_leaf_indices,2], c=colors_plot[non_leaf_indices], □
    ↪s=5, alpha=0.3)
ax.scatter(sampled_points_plot[leaf_indices,0], □
    ↪sampled_points_plot[leaf_indices,1], sampled_points_plot[leaf_indices,2], □
    ↪c=colors_plot[leaf_indices], s=10, marker='^', alpha=0.7)
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.tight_layout()
plt.show()

```



```
[28]: # plot 5 slices along the z axis, in 3d
z_min = np.min(orig_points[:,2])
z_max = np.max(orig_points[:,2])
slice_thickness = (z_max - z_min) / 7
z = z_min
```

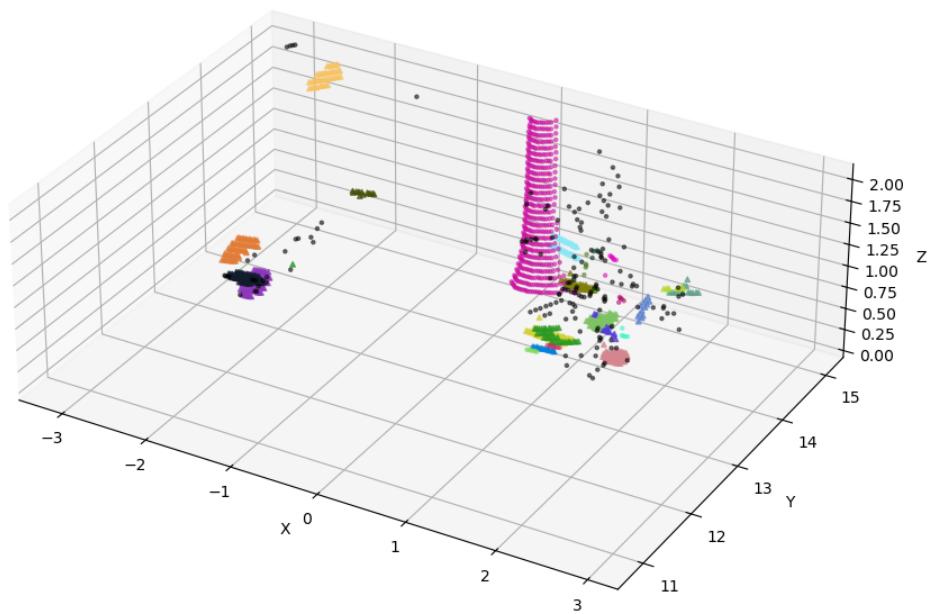
```

while z < z_max:
    # plot in 3d
    slice_points = orig_points[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_labels = new_labels[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_colors = np.array([label_to_color[label] for label in slice_labels])
    is_leaf_label_slice = is_leaf_label[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]

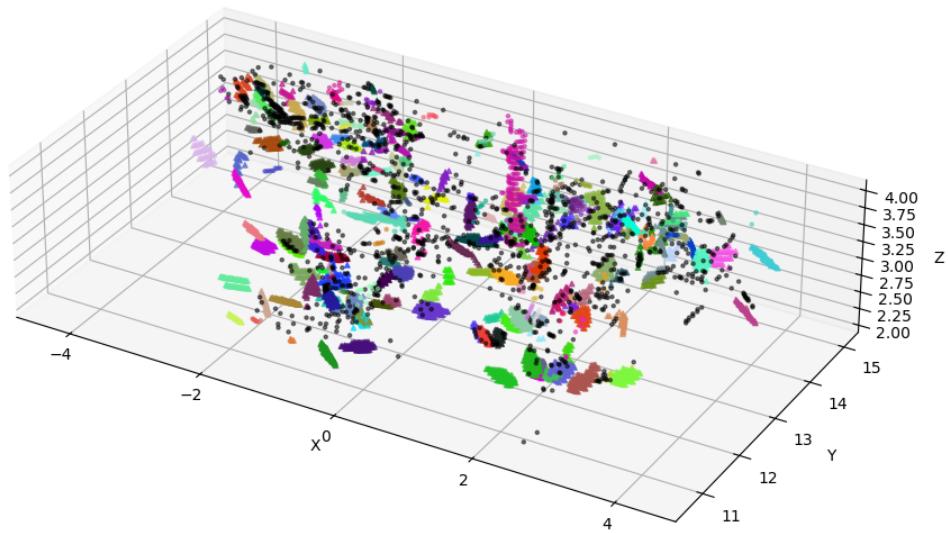
    fig = plt.figure(figsize=(10,8))
    ax = fig.add_subplot(111, projection='3d')
    # plot leaf by triangle
    ax.scatter(slice_points[~is_leaf_label_slice,0], slice_points[~is_leaf_label_slice,1], slice_points[~is_leaf_label_slice,2], c=slice_colors[~is_leaf_label_slice], s=5, alpha=0.5)
    ax.scatter(slice_points[is_leaf_label_slice,0], slice_points[is_leaf_label_slice,1], slice_points[is_leaf_label_slice,2], c=slice_colors[is_leaf_label_slice], s=10, marker='^', alpha=0.7)
    ax.set_xlabel('X')
    ax.set_ylabel('Y')
    ax.set_zlabel('Z')
    ax.set_aspect('equal', adjustable='box')
    plt.title(f'Slice along Z axis from {z:.2f} to {z + slice_thickness:.2f}')
    plt.tight_layout()
    plt.show()
    z += slice_thickness

```

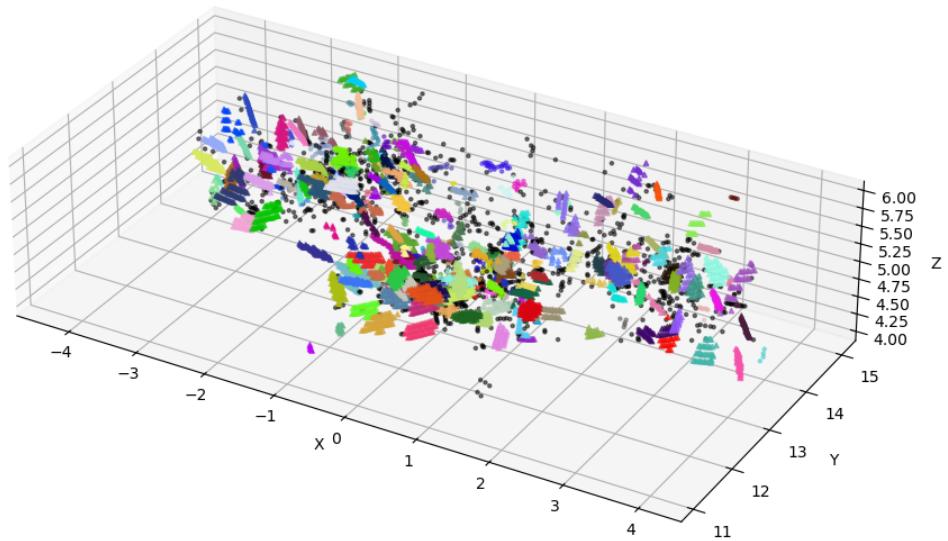
Slice along Z axis from 0.06 to 2.04



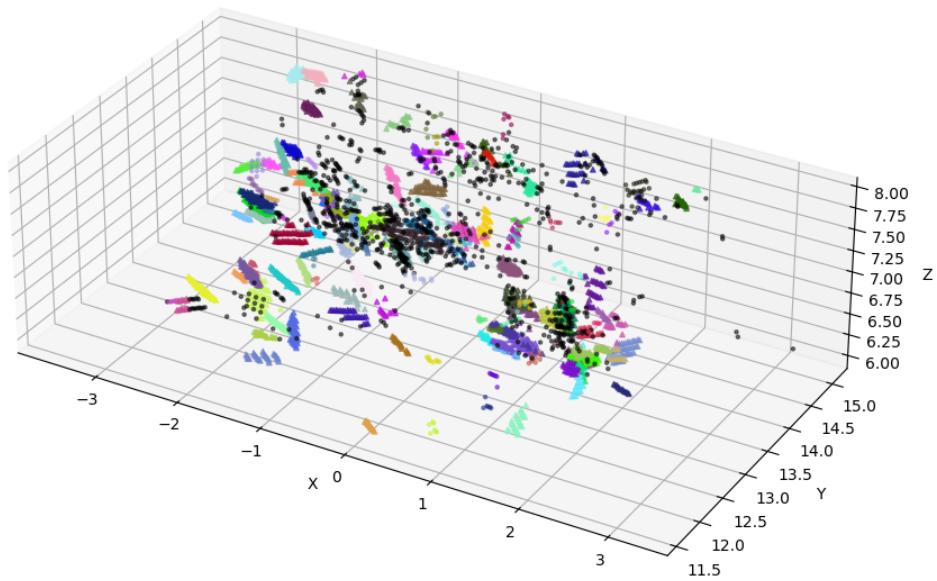
Slice along Z axis from 2.04 to 4.01



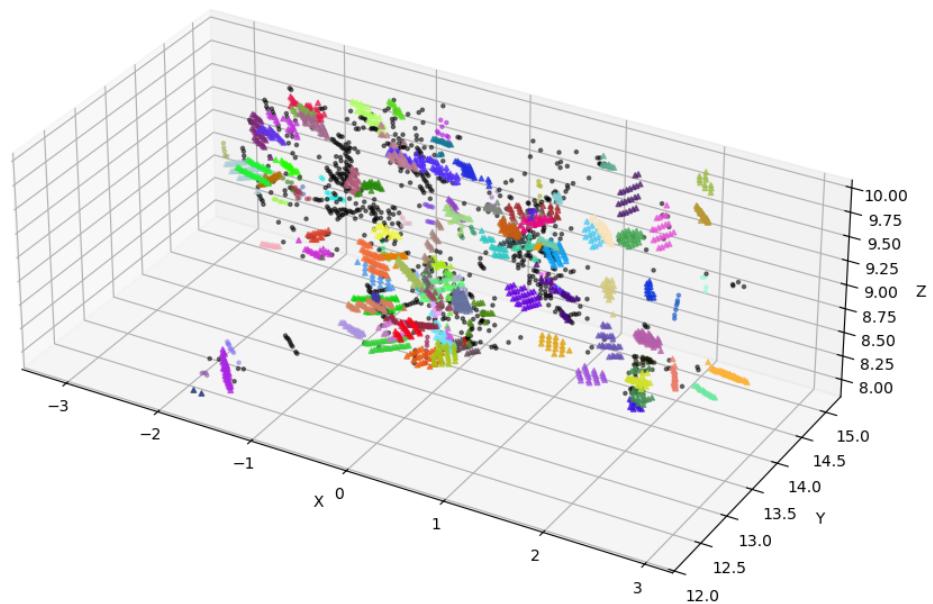
Slice along Z axis from 4.01 to 5.99



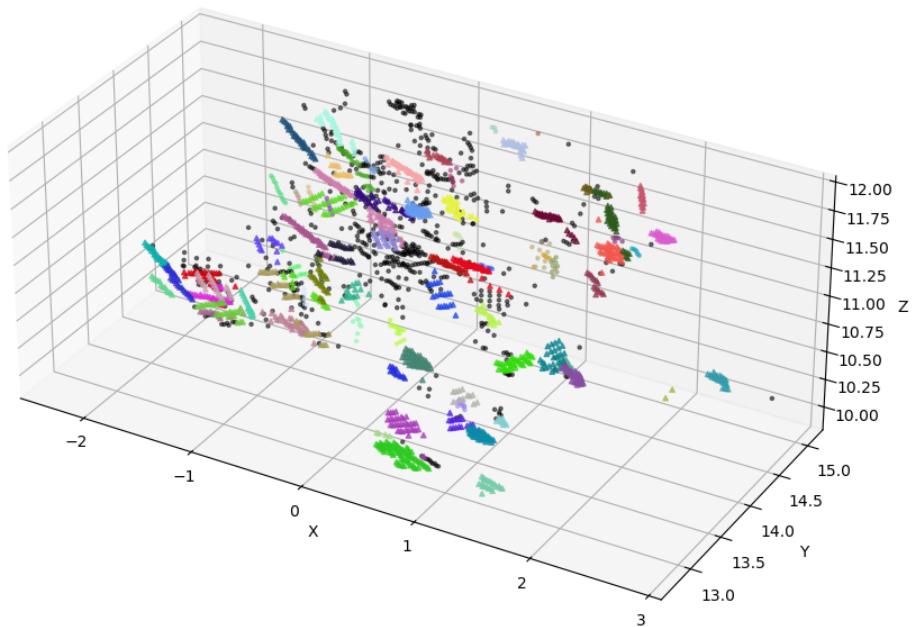
Slice along Z axis from 5.99 to 7.96



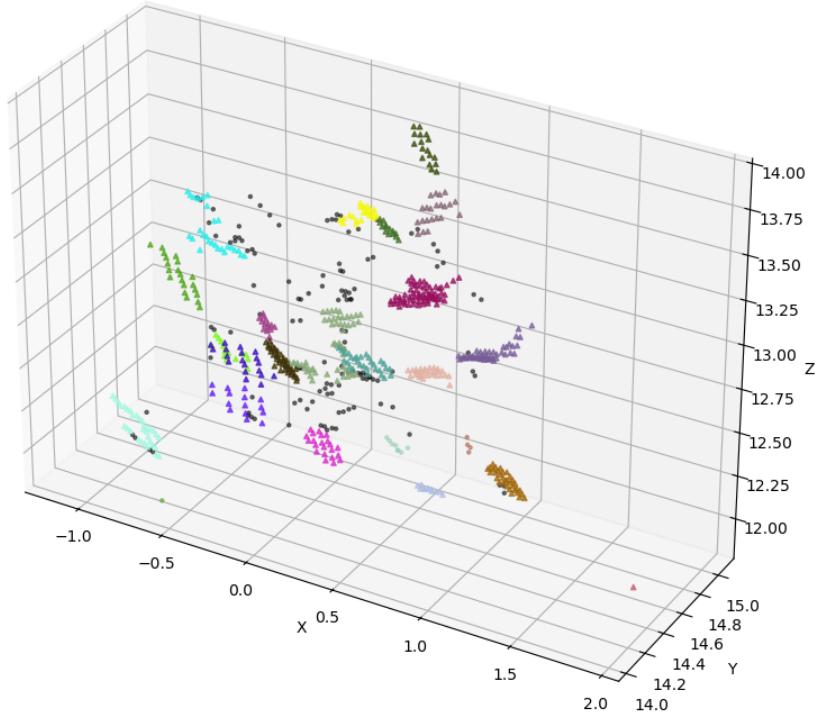
Slice along Z axis from 7.96 to 9.93



Slice along Z axis from 9.93 to 11.91



Slice along Z axis from 11.91 to 13.88



```
[29]: # assert False
```

6.1 Our estimation of number of leaves

```
[30]: # number of leaf clusters found is total number of num_leaf_cluster in ↴cluster_id_2_best_scales
num_leaf = 0
for k, v in cluster_id_2_best_scales.items():
    num_leaf += v[1]
print(f"Estimated total number of leaves: {num_leaf*2}") # because we estimate ↴on half of the point clouds
```

Estimated total number of leaves: 1092

```
[31]: # assert False
```

6.2 CT scan along z-axis

Triangle points is for leaf clusters and circle points is for branch clusters.

```
[32]: # plot the tree cutting along the z axis at different heights
z_min = np.min(orig_points[:,2])
z_max = np.max(orig_points[:,2])
slice_thickness = 0.51 / 0.3 # original thickness before scaling
z = z_min
while z < z_max:
    slice_points = orig_points[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_labels = new_labels[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_is_leaf = is_leaf_label[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]

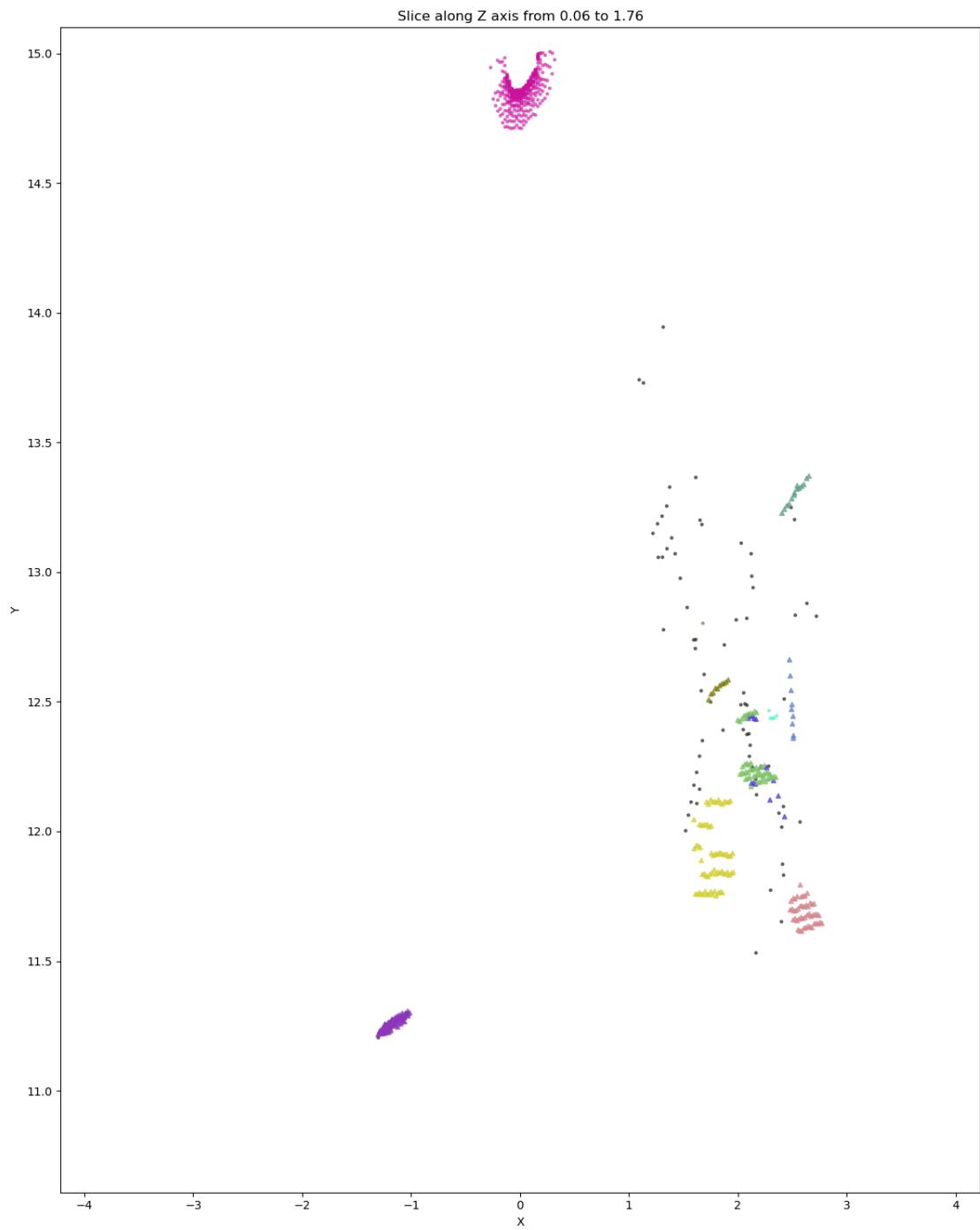
    # plot the slice with cluster colors
    fig = plt.figure(figsize=(12,15))
    ax = fig.add_subplot(111)

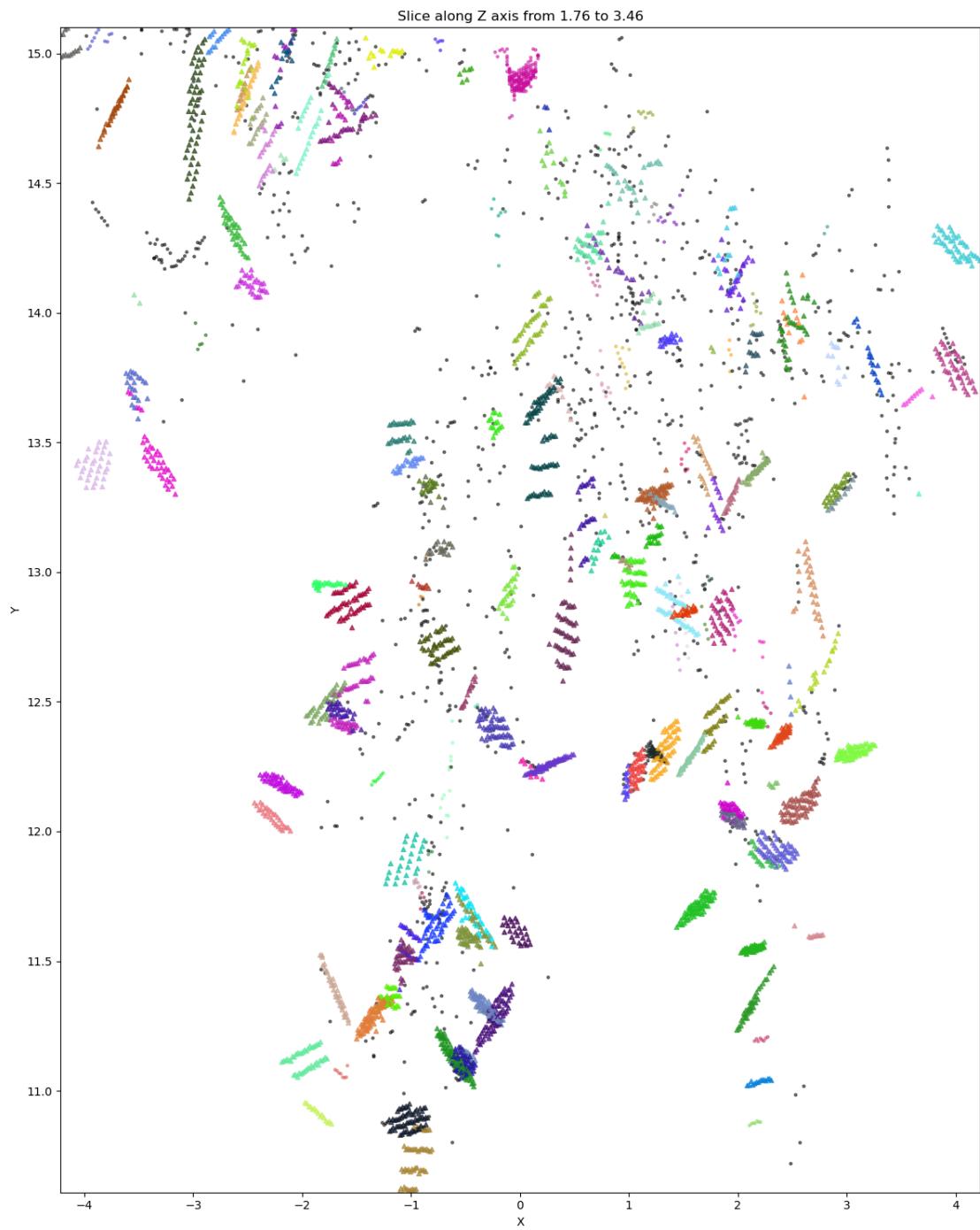
    slice_points_plot = slice_points
    slice_labels_plot = slice_labels

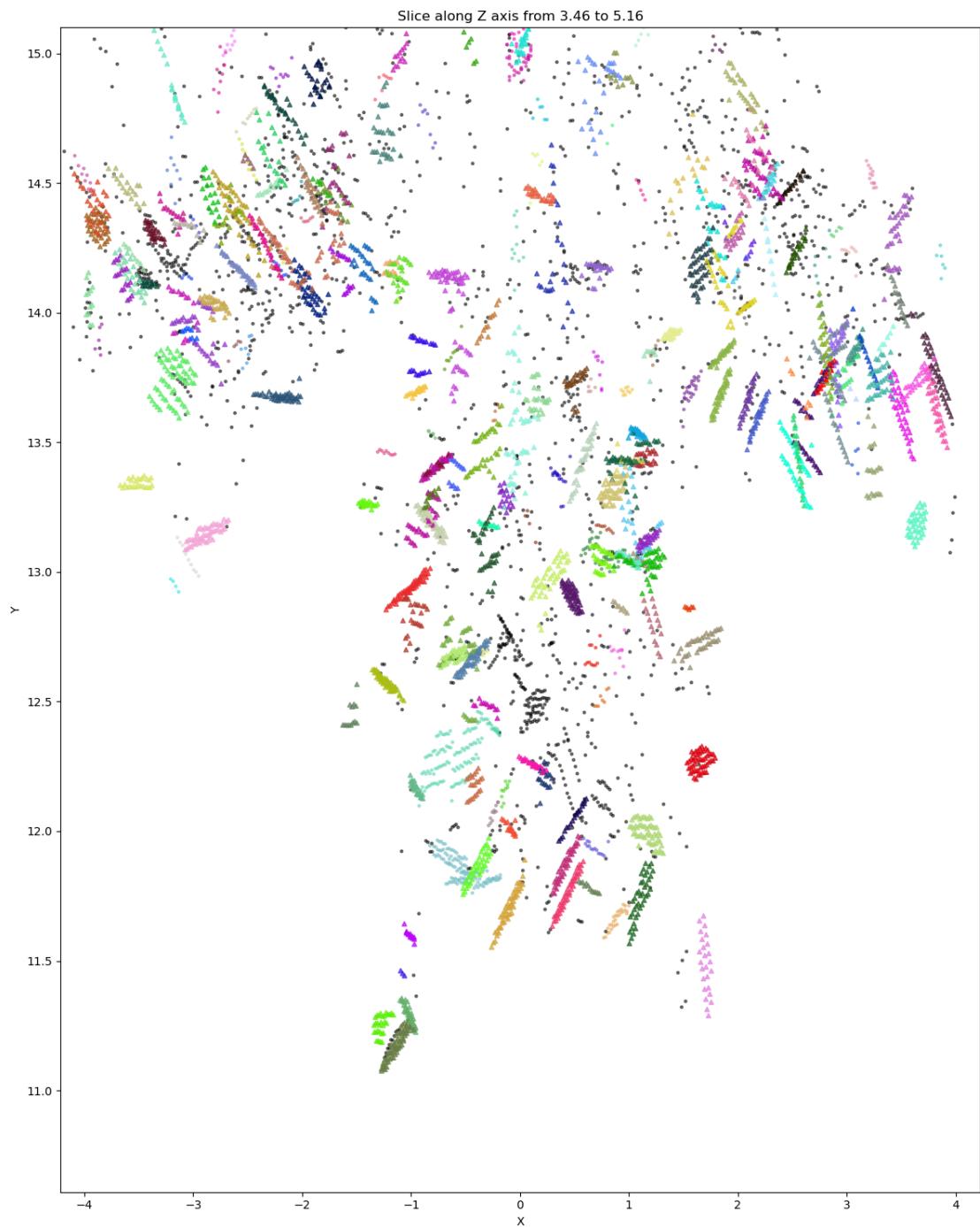
    colors_plot = np.array([label_to_color[label] for label in slice_labels_plot])

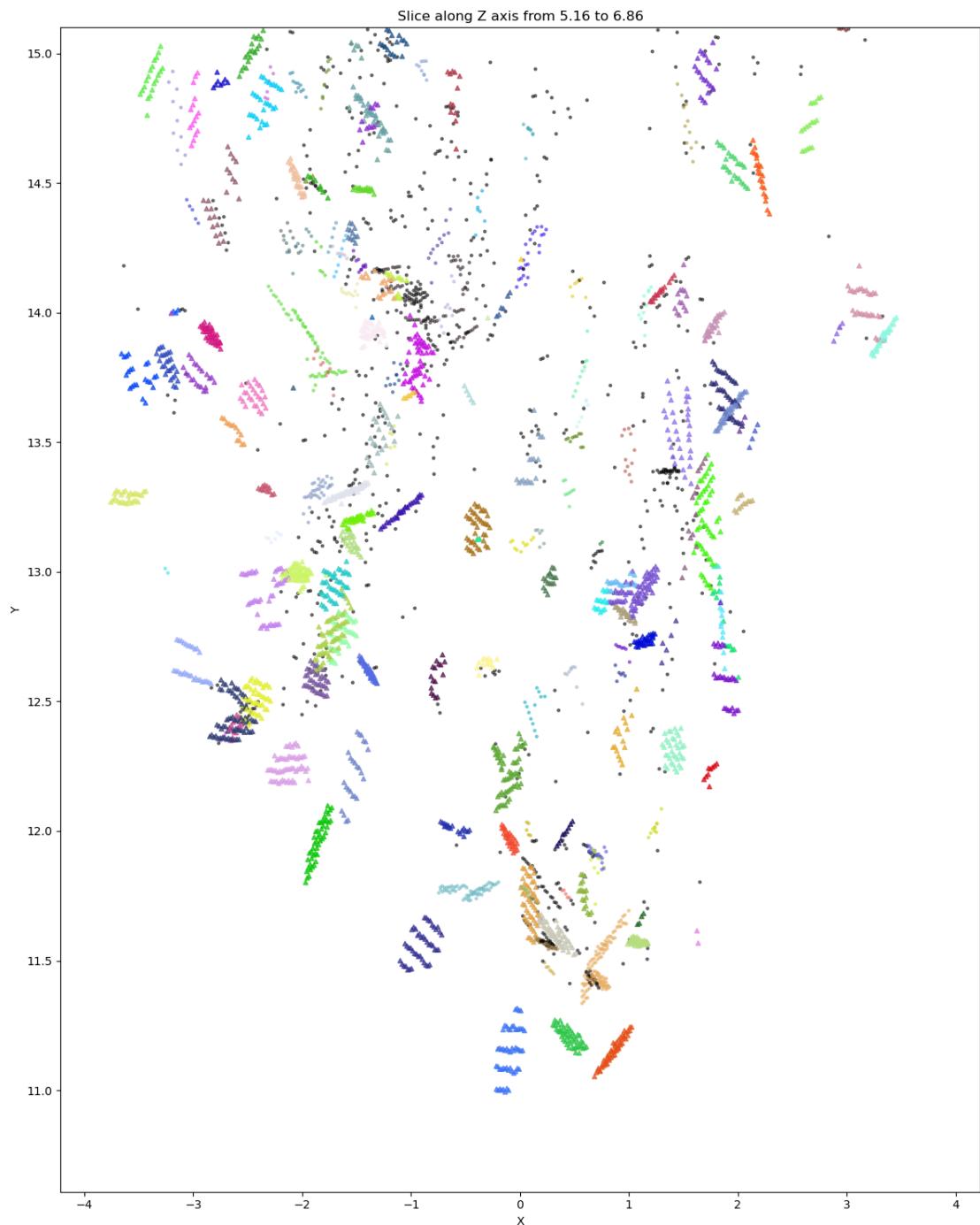
    # plot leaf points as triangles
    leaf_indices = slice_is_leaf
    non_leaf_indices = ~leaf_indices
    ax.scatter(slice_points_plot[non_leaf_indices,0], slice_points_plot[non_leaf_indices,1], c=colors_plot[non_leaf_indices], s=5, alpha=0.5)
    ax.scatter(slice_points_plot[leaf_indices,0], slice_points_plot[leaf_indices,1], c=colors_plot[leaf_indices], s=15, marker='^', alpha=0.7)
    ax.set_xlabel('X')
    ax.set_ylabel('Y')
    # ax.set_aspect('equal', adjustable='box')
    ax.set_xlim(np.min(orig_points[:,0]), np.max(orig_points[:,0]))
    ax.set_ylim(np.min(orig_points[:,1]), np.max(orig_points[:,1]))
    ax.set_title(f'Slice along Z axis from {z:.2f} to {z + slice_thickness:.2f}')
    plt.tight_layout()
    plt.show()

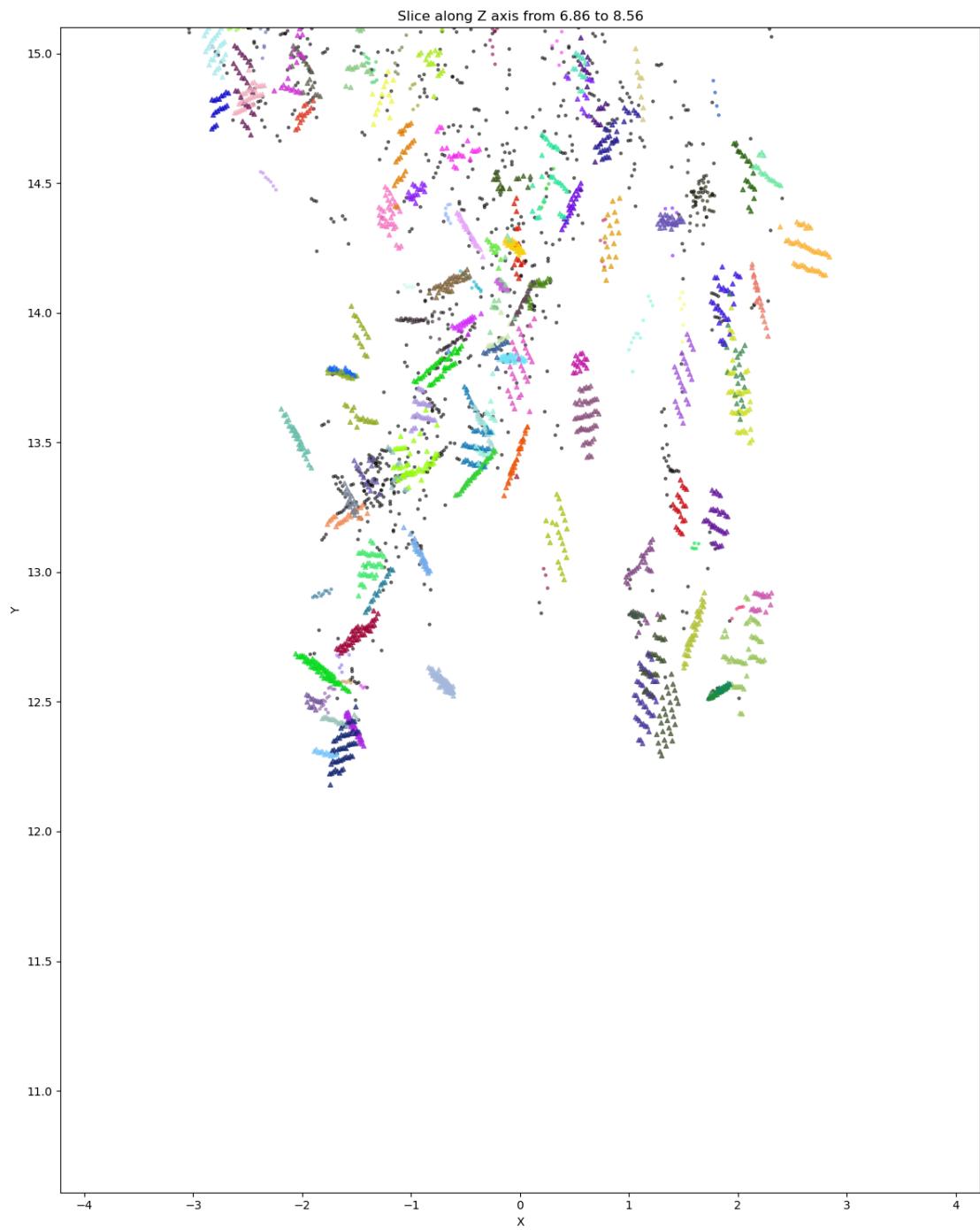
    z += slice_thickness
```

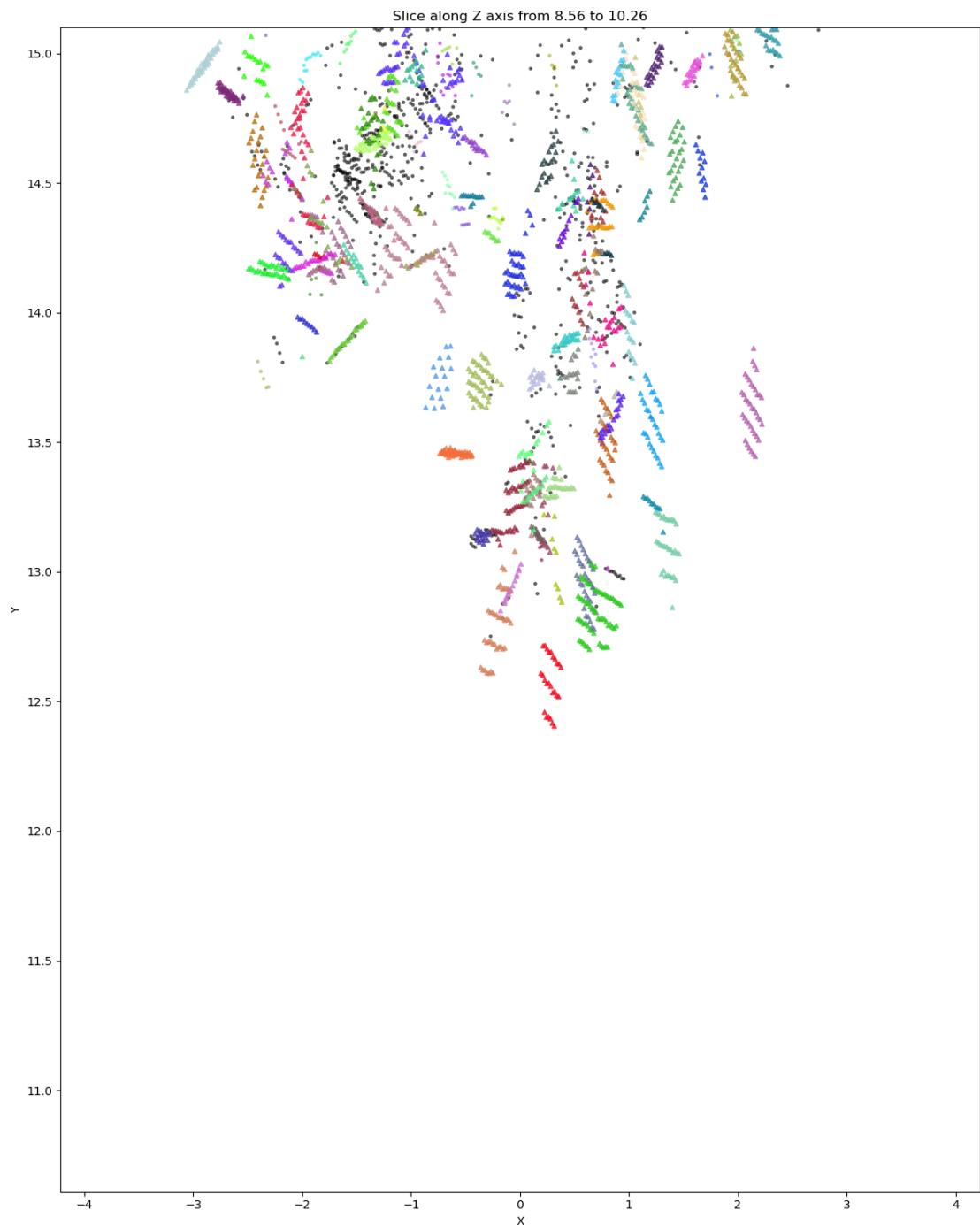


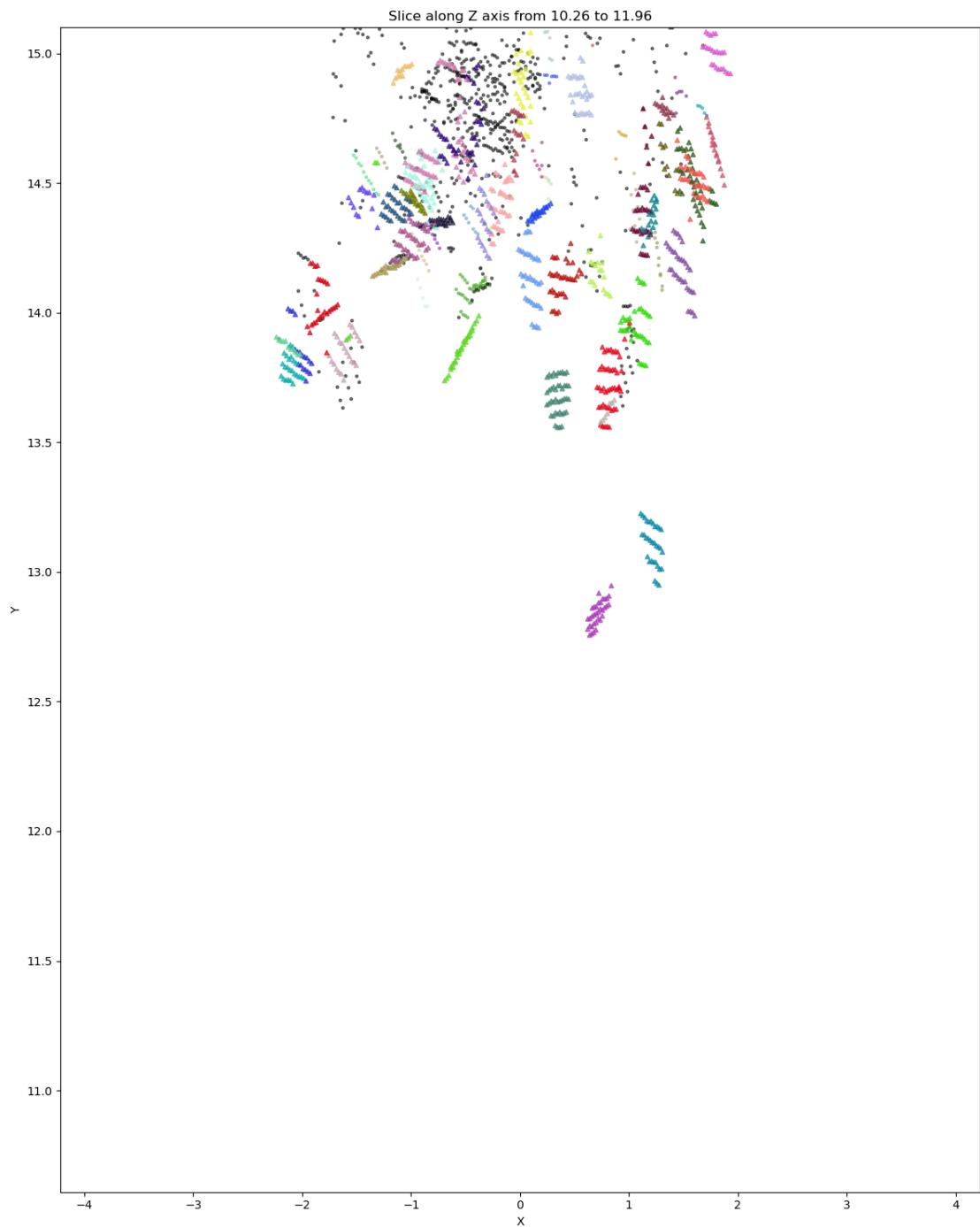


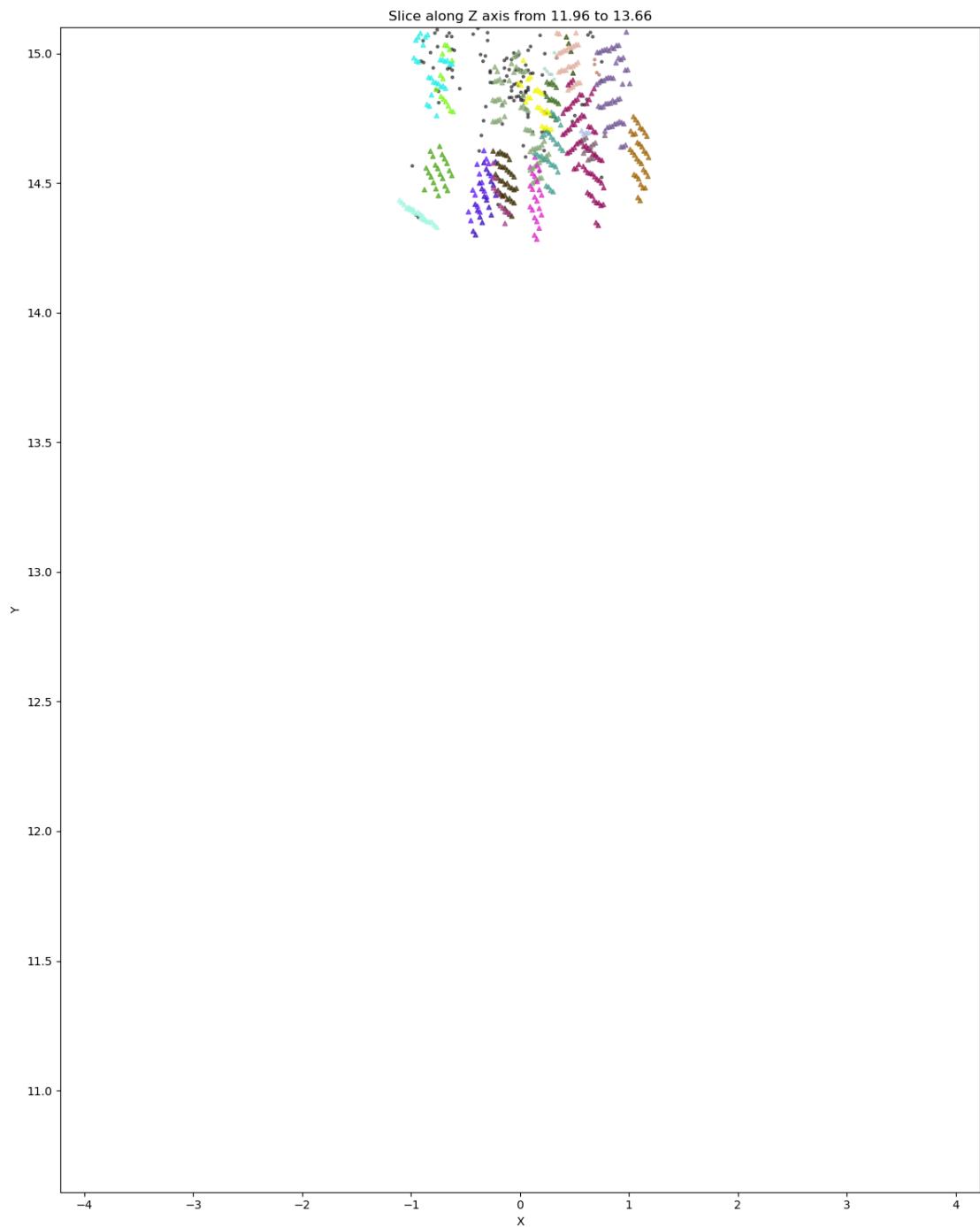


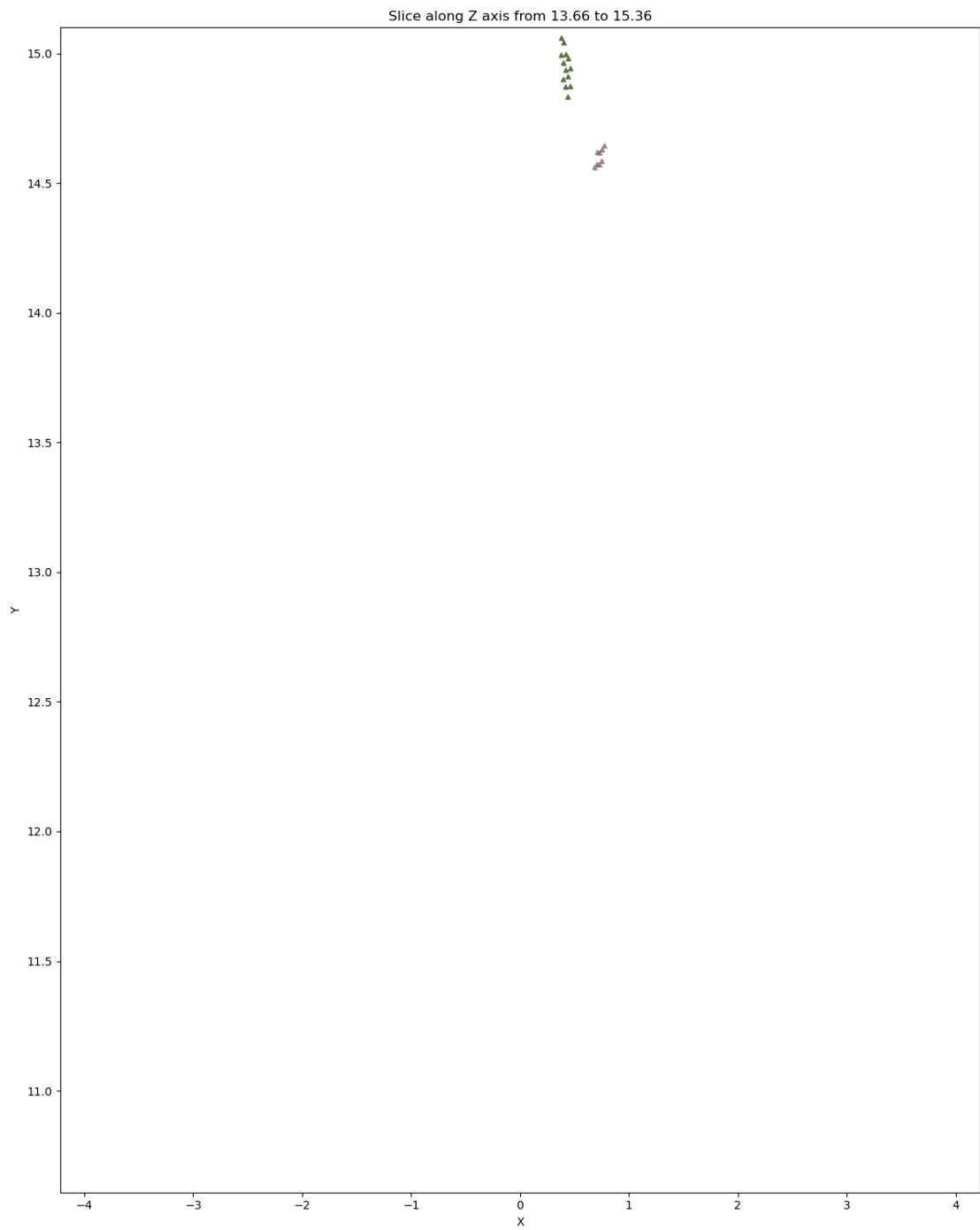












6.3 CT scan along y-axis

```
[33]: # slices along y axis
y_min = np.min(orig_points[:,1])
y_max = np.max(orig_points[:,1])
slice_thickness = 0.5 / 0.5 # original thickness before scaling
y = y_min
while y < y_max:
    slice_points = orig_points[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]
    slice_labels = new_labels[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]
    slice_is_leaf = is_leaf_label[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]

    # plot the slice with cluster colors
    fig = plt.figure(figsize=(12,15))
    ax = fig.add_subplot(111)
    # valid_indices = slice_labels != -1
    # slice_points_plot = slice_points[valid_indices]
    # slice_labels_plot = slice_labels[valid_indices]
    # leaf_indices = slice_is_leaf[valid_indices]

    slice_points_plot = slice_points
    slice_labels_plot = slice_labels
    leaf_indices = slice_is_leaf

    colors_plot = np.array([label_to_color[label] for label in slice_labels_plot])
    # plot leaf points as triangles

    non_leaf_indices = ~leaf_indices
    # # plot point where label is -1
    # noise_indices = slice_labels == -1
    # ax.scatter(slice_points=noise_indices,0], slice_points=noise_indices,2], c='gray', s=1, alpha=0.3)

    ax.scatter(slice_points_plot[non_leaf_indices,0], slice_points_plot[non_leaf_indices,2], c=colors_plot[non_leaf_indices], s=2, alpha=0.5)
    ax.scatter(slice_points_plot[leaf_indices,0], slice_points_plot[leaf_indices,2], c=colors_plot[leaf_indices], s=15, marker='^', alpha=0.7)
    # show cluster ids
    for label in set(slice_labels_plot):
        if label == -1:
            continue
```

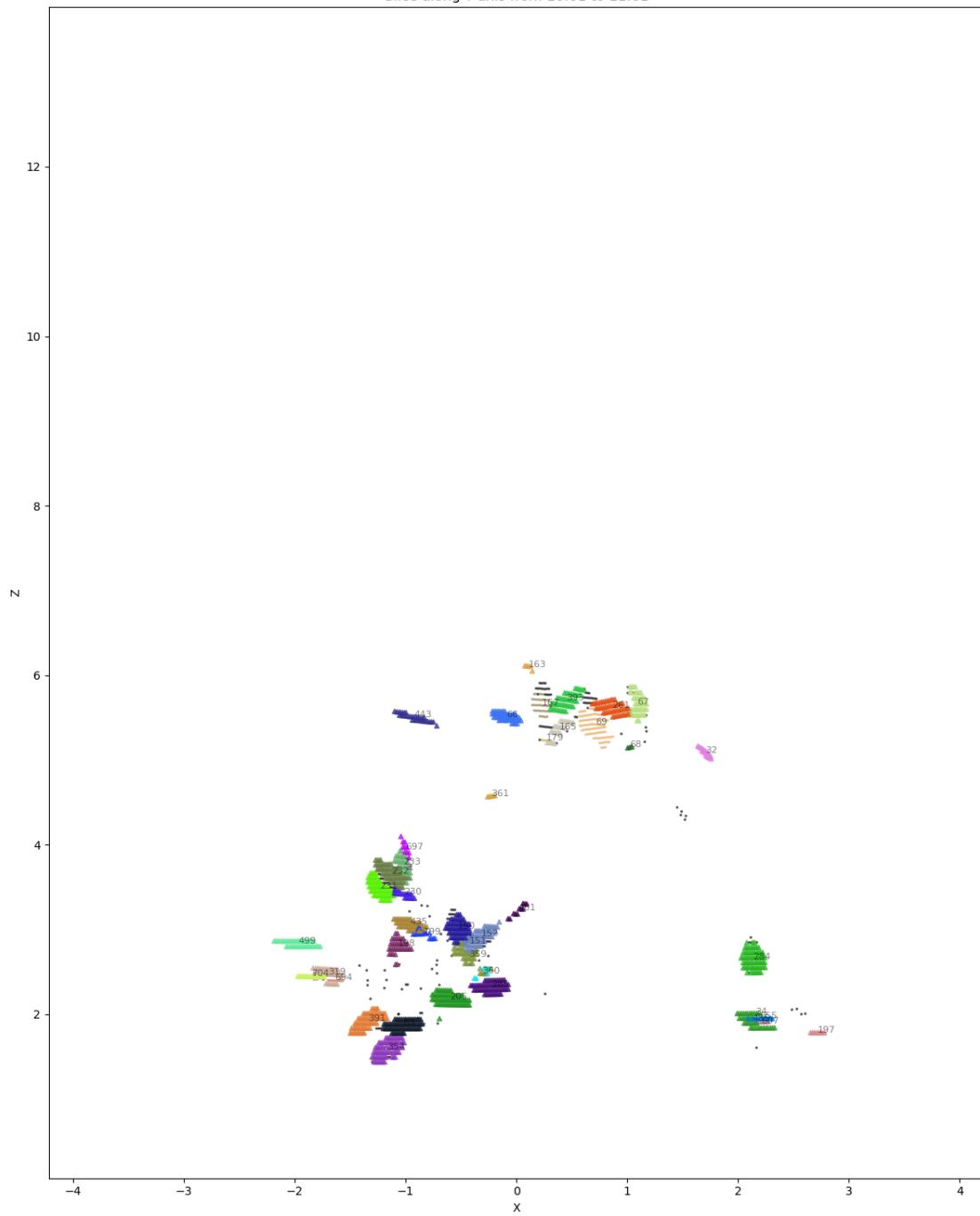
```

label_indices = slice_labels_plot == label
if np.sum(label_indices) == 0:
    continue
mean_x = np.mean(slice_points_plot[label_indices,0])
mean_z = np.mean(slice_points_plot[label_indices,2])
ax.text(mean_x, mean_z, str(label), color='black', fontsize=8, alpha=0.
˓→5)
ax.set_xlabel('X')
ax.set_ylabel('Z')
# ax.set_aspect('equal', adjustable='box')
ax.set_xlim(np.min(orig_points[:,0]), np.max(orig_points[:,0]))
ax.set_ylim(np.min(orig_points[:,2]), np.max(orig_points[:,2]))
ax.set_title(f'Slice along Y axis from {y:.2f} to {y + slice_thickness:.
˓→2f}')
plt.tight_layout()
plt.show()

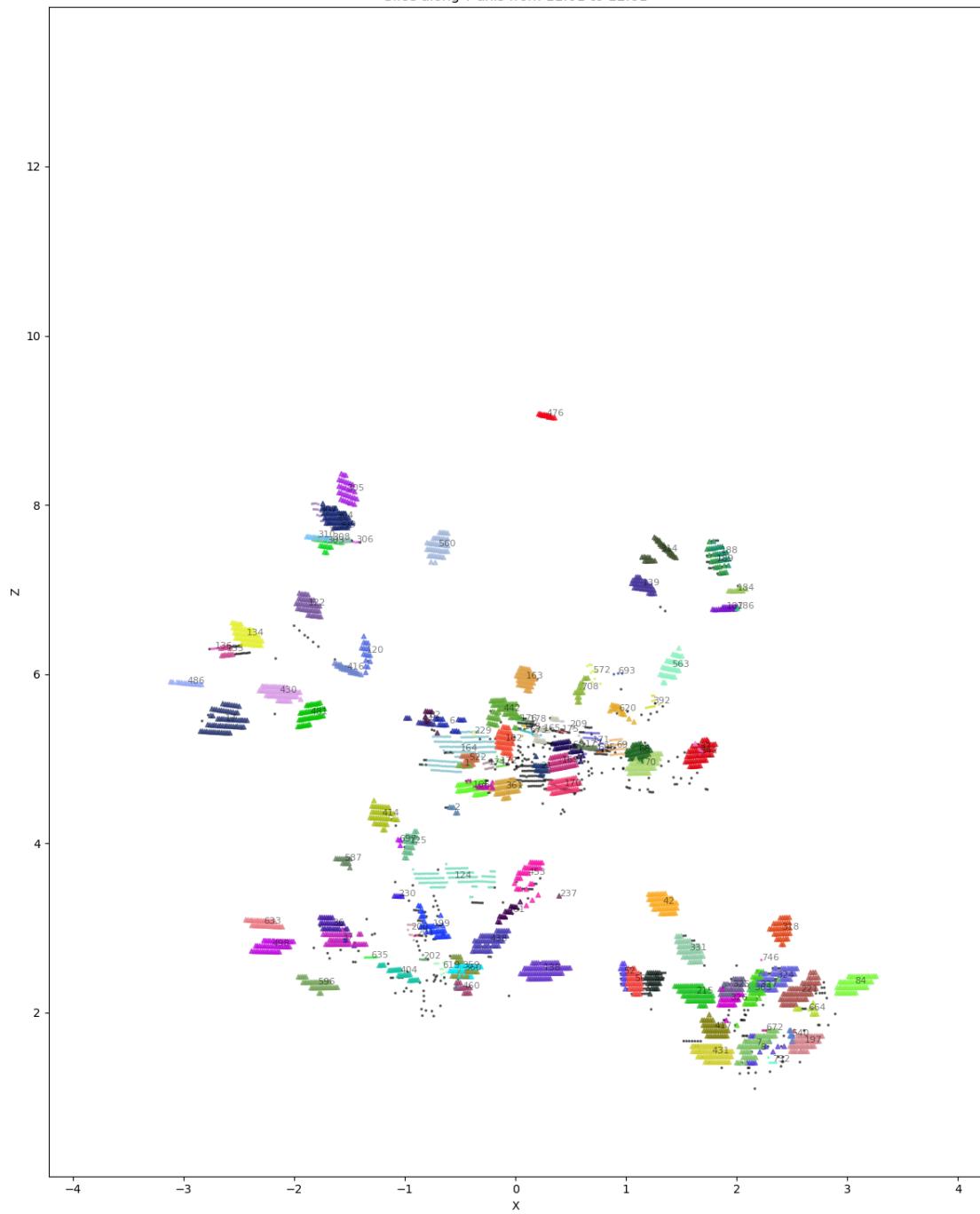
y += slice_thickness

```

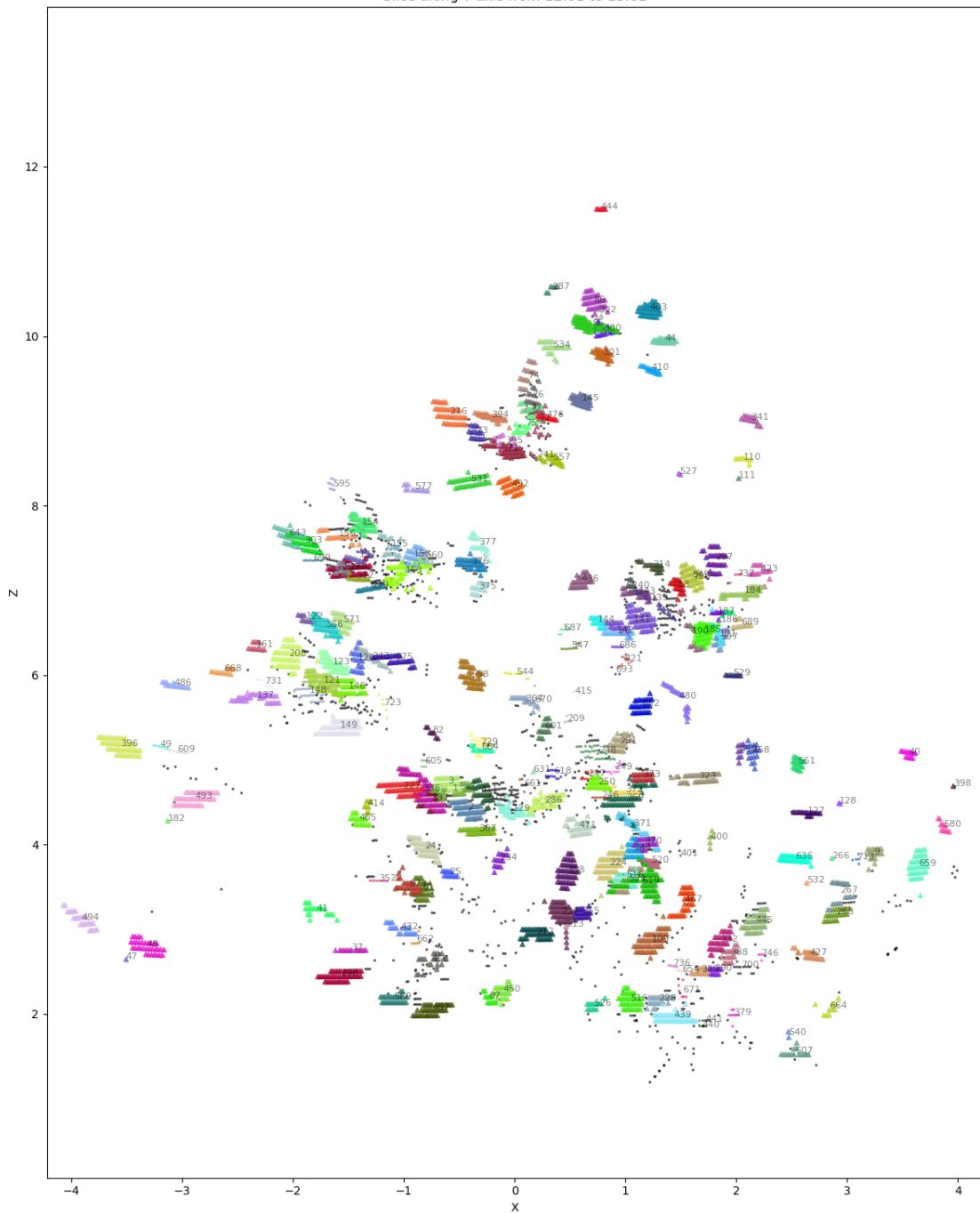
Slice along Y axis from 10.61 to 11.61

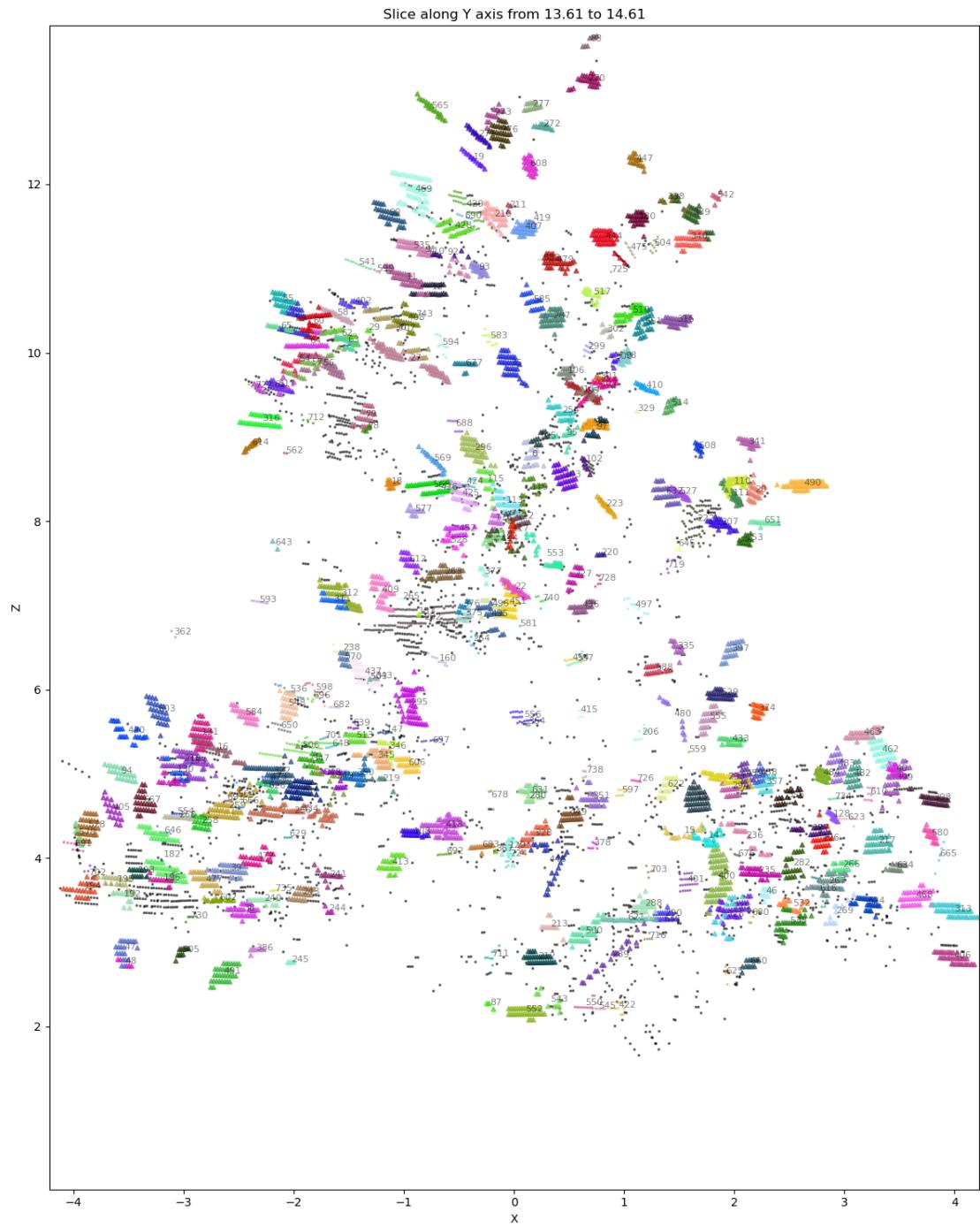


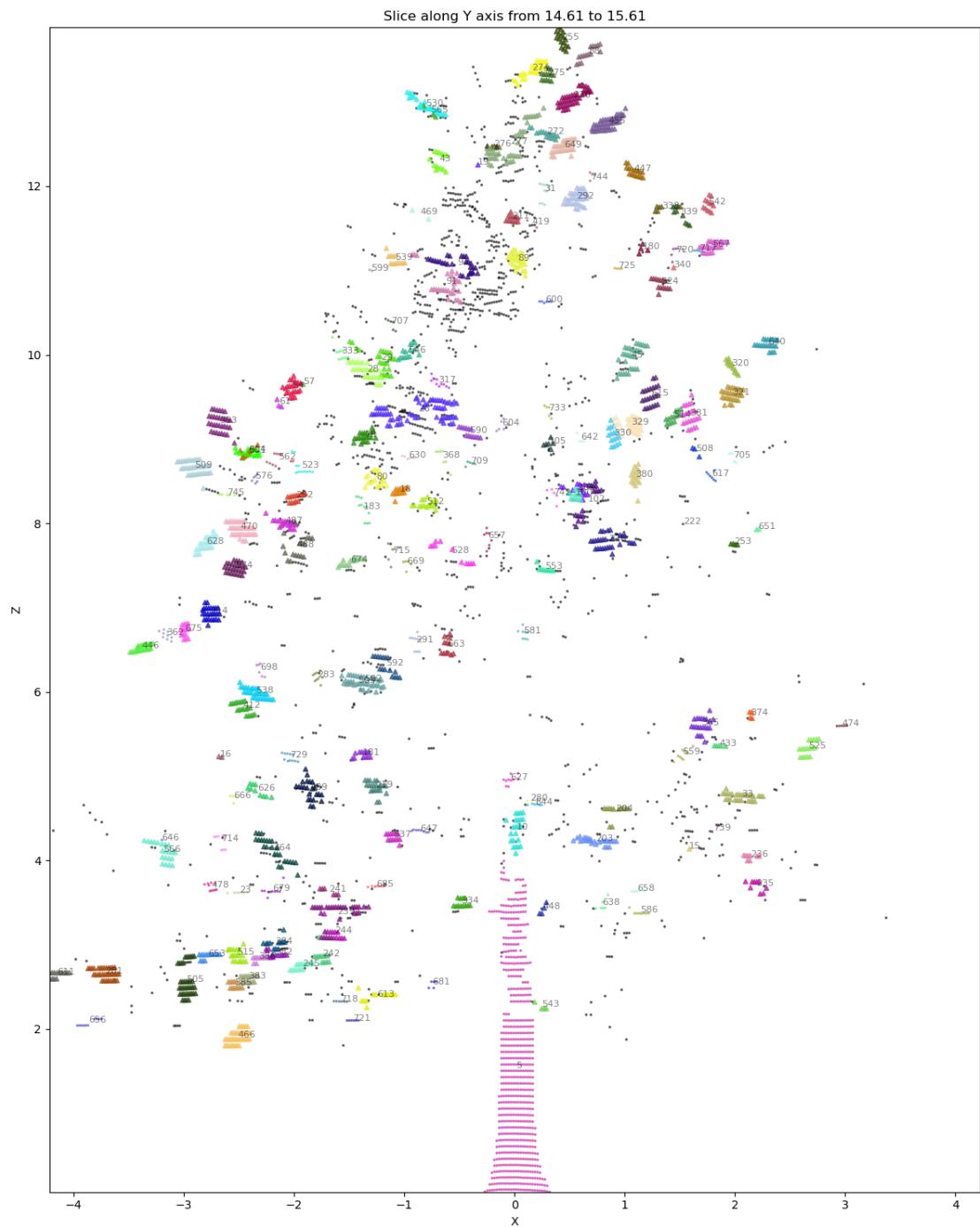
Slice along Y axis from 11.61 to 12.61



Slice along Y axis from 12.61 to 13.61







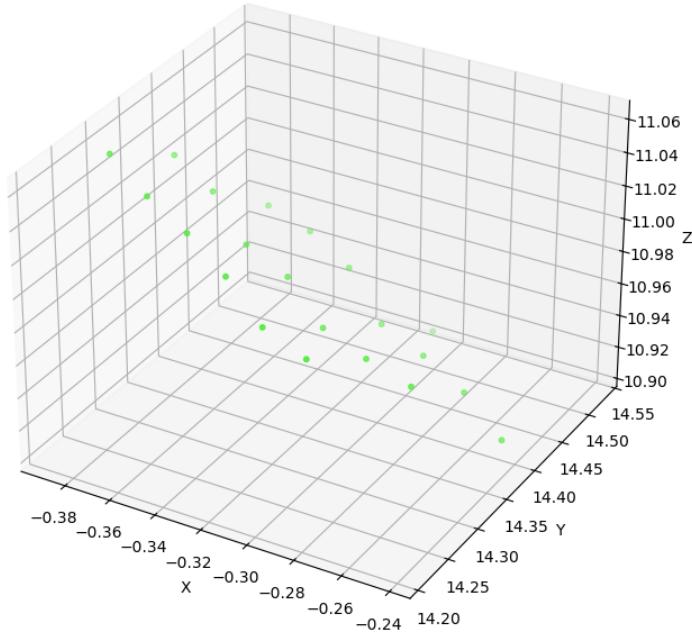
7 Inspect some leaf clusters

```
[34]: # plot 3d scatter of leaf clusters only
inspect_cluster_id = 93
leaf_points = orig_points[(new_labels == inspect_cluster_id)]
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
ax.scatter(leaf_points[:,0], leaf_points[:,1], leaf_points[:,2], s=10,
           c=colors_plot[inspect_cluster_id])
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.title(f'Leaf Cluster ID: {inspect_cluster_id}, Number of points: {leaf_points.shape[0]}, is_leaf: {is_leaf_label[new_labels == inspect_cluster_id].all()}')
plt.show()
```

/tmp/ipykernel_1610924/1856379671.py:6: UserWarning: *c* argument looks like a single numeric RGB or RGBA sequence, which should be avoided as value-mapping will have precedence in case its length matches with **x** & **y**. Please use the *color* keyword-argument or provide a 2D array with a single row if you intend to specify the same RGB or RGBA value for all points.

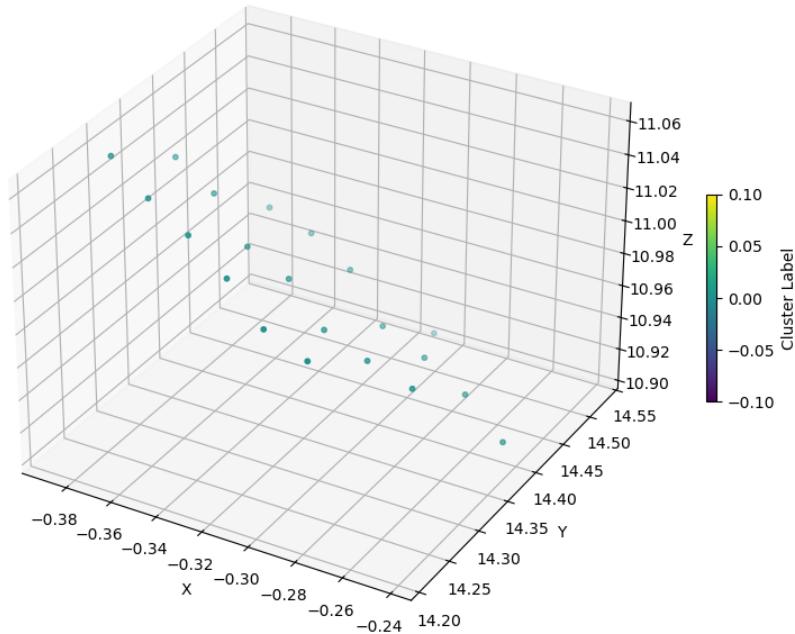
```
    ax.scatter(leaf_points[:,0], leaf_points[:,1], leaf_points[:,2], s=10,
               c=colors_plot[inspect_cluster_id])
```

Leaf Cluster ID: 93, Number of points: 21, is_leaf: True



```
[35]: # try running dbscan
best_score, best_num_leaf_clusters, clustering_assignment, leaf_labels =
    DBSCAN_cluster_optimization(leaf_points, plane_threshold=0.04)
# plot the clustering result
fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')
sc = ax.scatter(leaf_points[:,0], leaf_points[:,1], leaf_points[:,2],
    c=clustering_assignment, cmap='viridis', s=10)
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
plt.colorbar(sc, ax=ax, label='Cluster Label', shrink=0.3)
plt.title(f'Leaf Cluster ID: {inspect_cluster_id} DBSCAN Subclustering Result')
plt.show()
```

Leaf Cluster ID: 93 DBSCAN Subclustering Result



[]:

8 Compute leaf area

```
[36]: # for each leaf cluster, divide it to to triangles using Delaunay triangulation
      ↵and compute area by summing triangle areas
from scipy.spatial import ConvexHull
leaf_areas = []
leaf_largest_distances = []
cluster_label_2_area = {}
cluster_label_2_largest_distance = {}
count = 0
for cluster_label in set(new_labels):
    if cluster_label == -1:
        continue # skip noise

    points = orig_points[new_labels == cluster_label]
    is_leaf = is_leaf_label[new_labels == cluster_label]
```

```

# assert is_leaf is all True or all False
try:
    assert np.all(is_leaf) or not np.any(is_leaf)
except AssertionError:
    print(f"Cluster {cluster_label} has mixed leaf labels.")
    print(is_leaf)
    continue

# print(is_leaf)
if not np.all(is_leaf):
    continue # not a leaf cluster

# compute delaunay triangulation in 3D
try:
    hull = ConvexHull(points)
except:
    print(f"Cluster {cluster_label} cannot find convex hull.")
    continue # skip clusters that cannot be triangulated

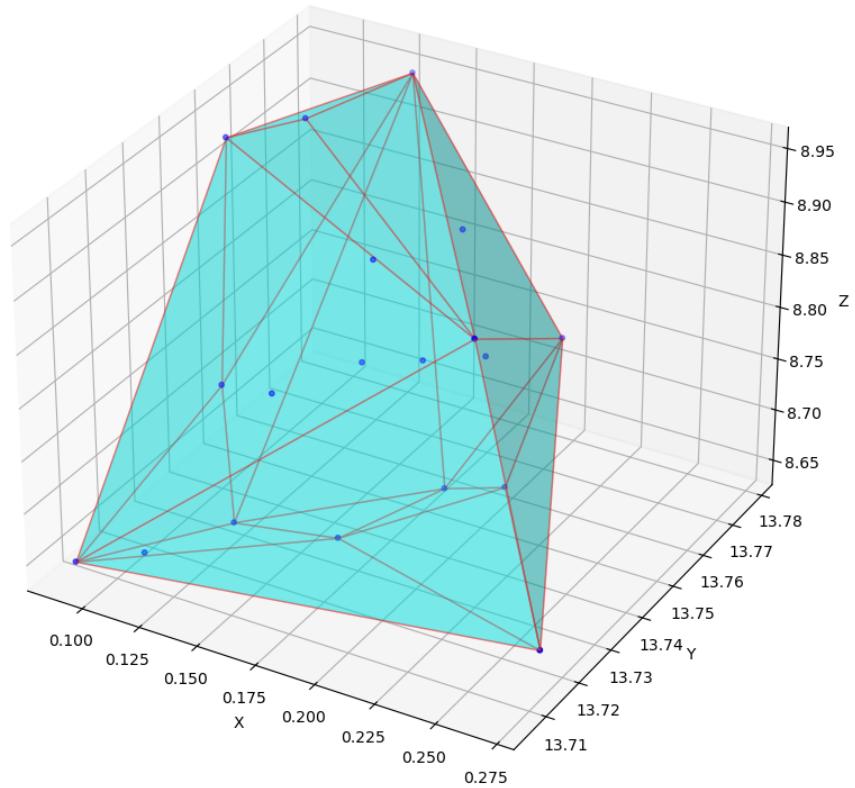
# compute largest distance between points in the cluster
from scipy.spatial.distance import pdist
largest_distance = np.max(pdist(points))
cluster_label_2_largest_distance[cluster_label] = largest_distance
leaf_largest_distances.append(largest_distance)

# plot triangulation
if count <= 5:
    fig = plt.figure(figsize=(10,10))
    ax = fig.add_subplot(111, projection='3d')
    ax.scatter(points[:,0], points[:,1], points[:,2], s=10, color='b')
    for simplex in hull.simplices:
        tri_points = points[simplex]
        ax.plot_trisurf(tri_points[:,0], tri_points[:,1], tri_points[:,2], color='cyan', alpha=0.3, edgecolor='r')
    ax.set_xlabel('X')
    ax.set_ylabel('Y')
    ax.set_zlabel('Z')
    plt.title(f'Convex Hull of Leaf Cluster {cluster_label}')
    plt.show()
count += 1

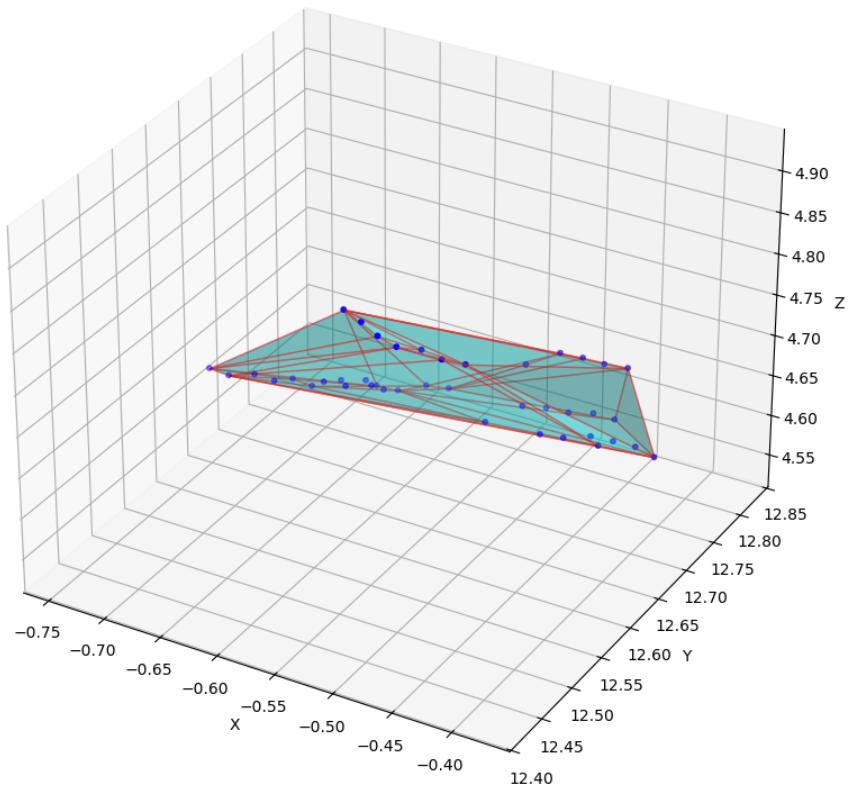
# compute area of each triangle
area = hull.area / 2.0 # Leaf area is half of the convex hull area
leaf_areas.append(area)
cluster_label_2_area[cluster_label] = area

```

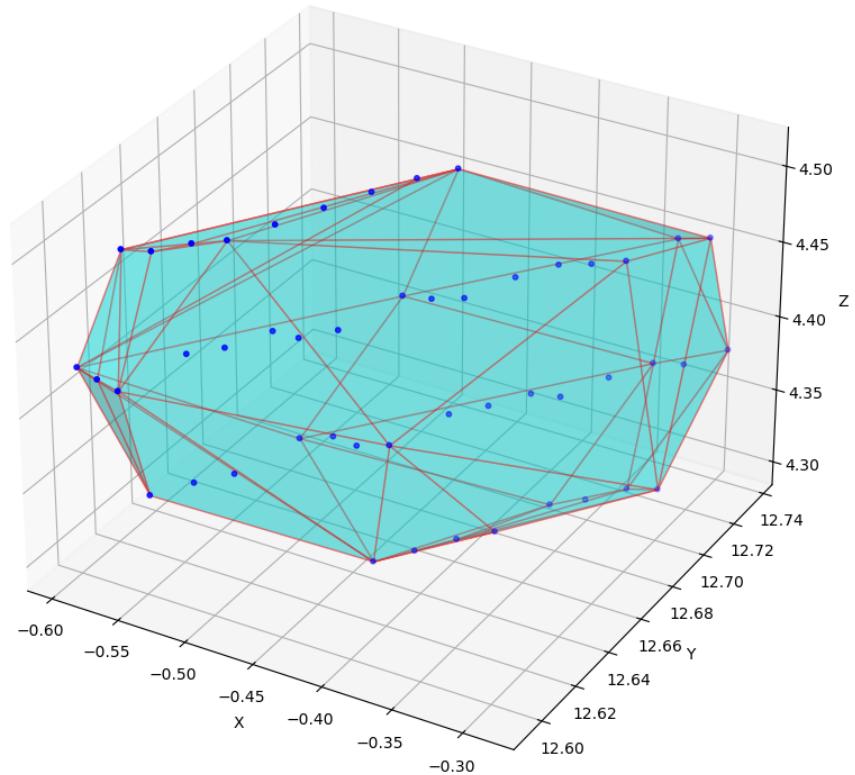
Convex Hull of Leaf Cluster 0



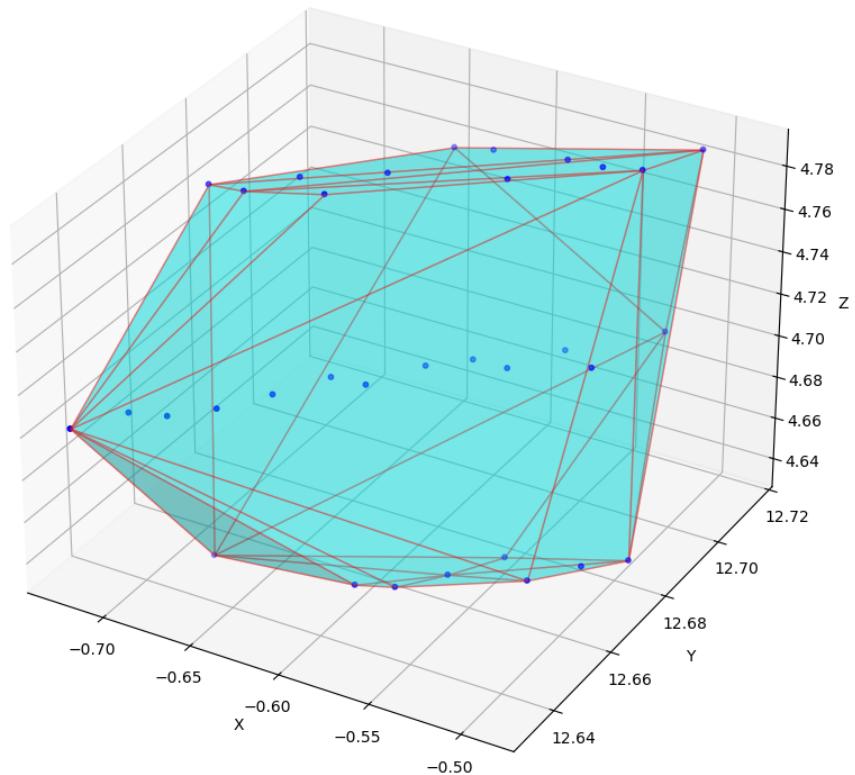
Convex Hull of Leaf Cluster 1



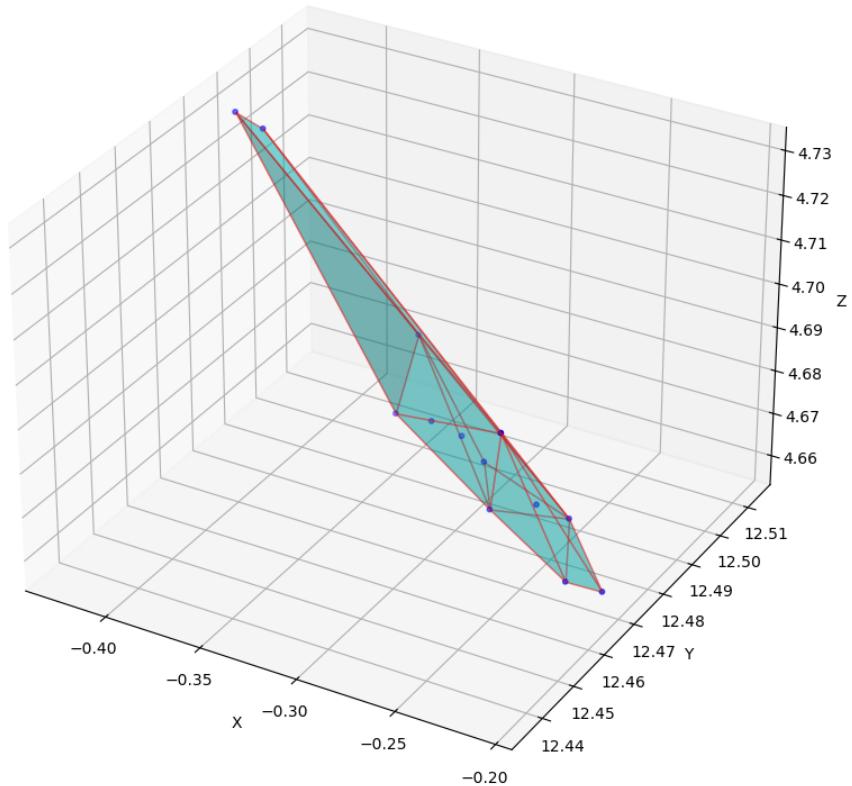
Convex Hull of Leaf Cluster 2



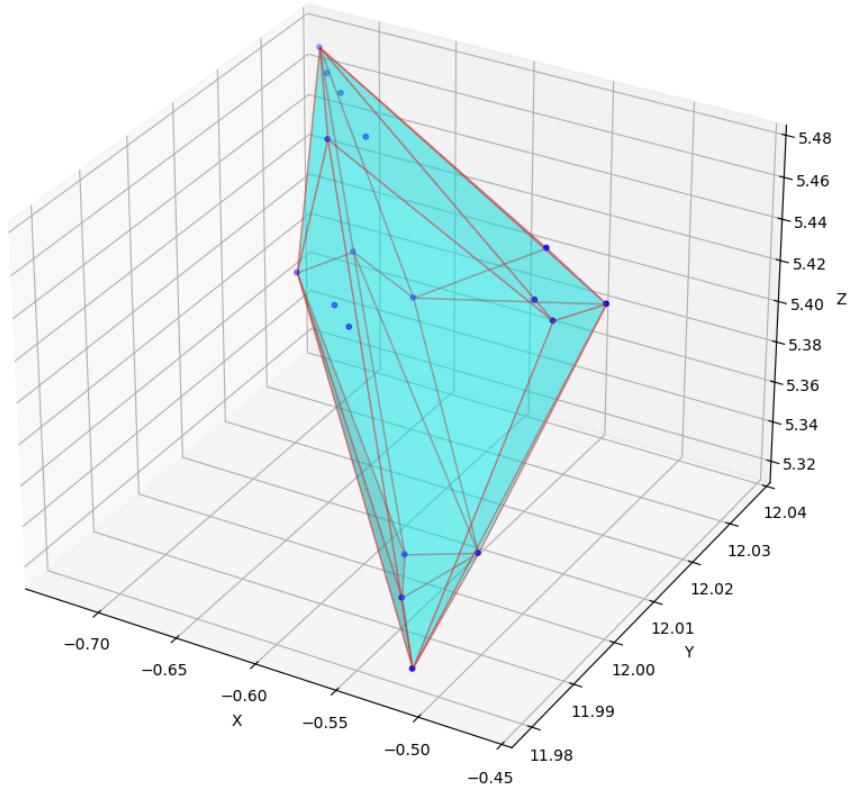
Convex Hull of Leaf Cluster 3



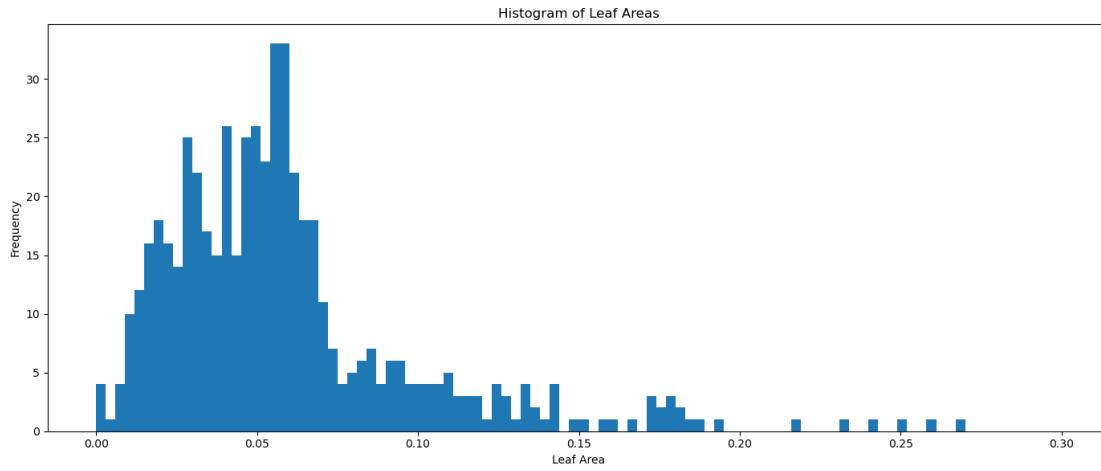
Convex Hull of Leaf Cluster 4



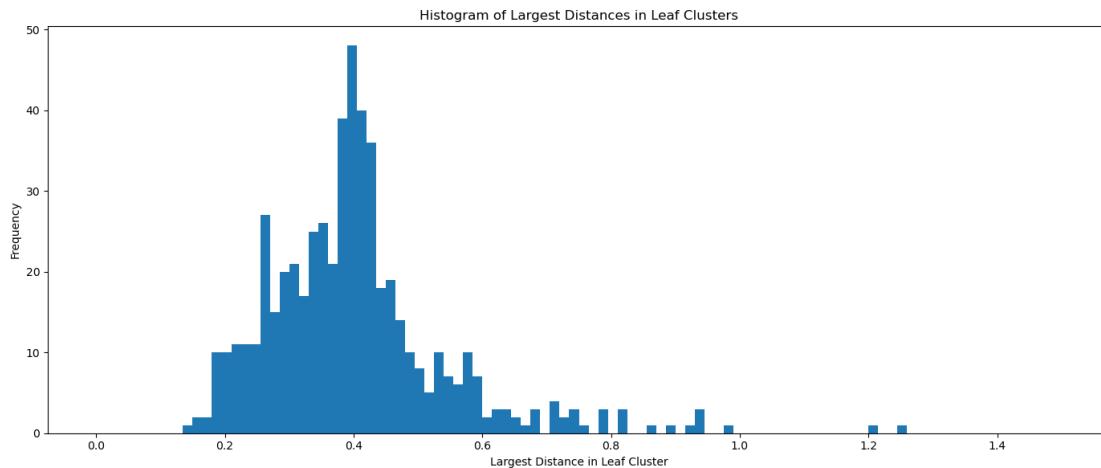
Convex Hull of Leaf Cluster 6



```
[37]: # plot histogram of leaf areas
plt.figure(figsize=(14,6))
plt.hist(leaf_areas, bins=100, range=(0, 0.3))
plt.xlabel('Leaf Area')
plt.ylabel('Frequency')
plt.title('Histogram of Leaf Areas')
plt.tight_layout()
plt.show()
```



```
[38]: # plot histogram of largest distances
plt.figure(figsize=(14,6))
plt.hist(list(cluster_label_2_largest_distance.values()), bins=100, range=(0, 1.5))
plt.xlabel('Largest Distance in Leaf Cluster')
plt.ylabel('Frequency')
plt.title('Histogram of Largest Distances in Leaf Clusters')
plt.tight_layout()
plt.show()
```



The leaves which have area above 0.15 m^2 are very suspicious, so we calculate the total leaf area excluding those leaves.

```
[39]: # total leaf area
leaf_area_threshold = 0.15 # We accept case where there is 2 leaves merged together
leaf_lower_bound = 0.01
leaf_distance_threshold = 1.0 # just in case there are 2 merged leaves
leaf_areas = np.array(leaf_areas)
leaf_largest_distances = np.array(leaf_largest_distances)

total_leaf_area = np.sum(
    leaf_areas[(leaf_areas < leaf_area_threshold) & (leaf_areas > leaf_lower_bound) & (leaf_largest_distances < leaf_distance_threshold)])
print(f"Estimated total leaf area (excluding leaves with area > {leaf_area_threshold} m^2): {total_leaf_area * 2:.2f} m^2")
print(f"Estimated number of leaves: {len(leaf_areas[(leaf_areas < leaf_area_threshold) & (leaf_areas > leaf_lower_bound) & (leaf_largest_distances < leaf_distance_threshold)])*2}")
```

Estimated total leaf area (excluding leaves with area > 0.15 m²): 55.10 m²
 Estimated number of leaves: 1018

```
[40]: leaf_areas_column = []
for label in new_labels:
    if label in cluster_label_2_area:
        leaf_areas_column.append(cluster_label_2_area[label])
    else:
        leaf_areas_column.append(0.0)
leaf_areas_column = np.array(leaf_areas_column)

leaf_largest_distances_column = []
for label in new_labels:
    if label in cluster_label_2_largest_distance:
        leaf_largest_distances_column.append(cluster_label_2_largest_distance[label])
    else:
        leaf_largest_distances_column.append(0.0)
leaf_largest_distances_column = np.array(leaf_largest_distances_column)
```

```
[41]: # re plot the tree, remove is_leaf points which have area > 0.2 m^2
```

```
# plot tree using new labels
fig = plt.figure(figsize=(11,15))
ax = fig.add_subplot(111, projection='3d')
# remove points which belong to no cluster (label = -1)
valid_indices = new_labels != -1
sampled_points_plot = orig_points[valid_indices]
labels_plot = new_labels[valid_indices]
colors_plot = np.array([label_to_color[label] for label in labels_plot])
```

```

# plot leaf points as triangles
leaf_indices = is_leaf_label[valid_indices] & (leaf_areas_column[valid_indices] <
    leaf_area_threshold ) &\

    (leaf_largest_distances_column[valid_indices] < leaf_distance_threshold)

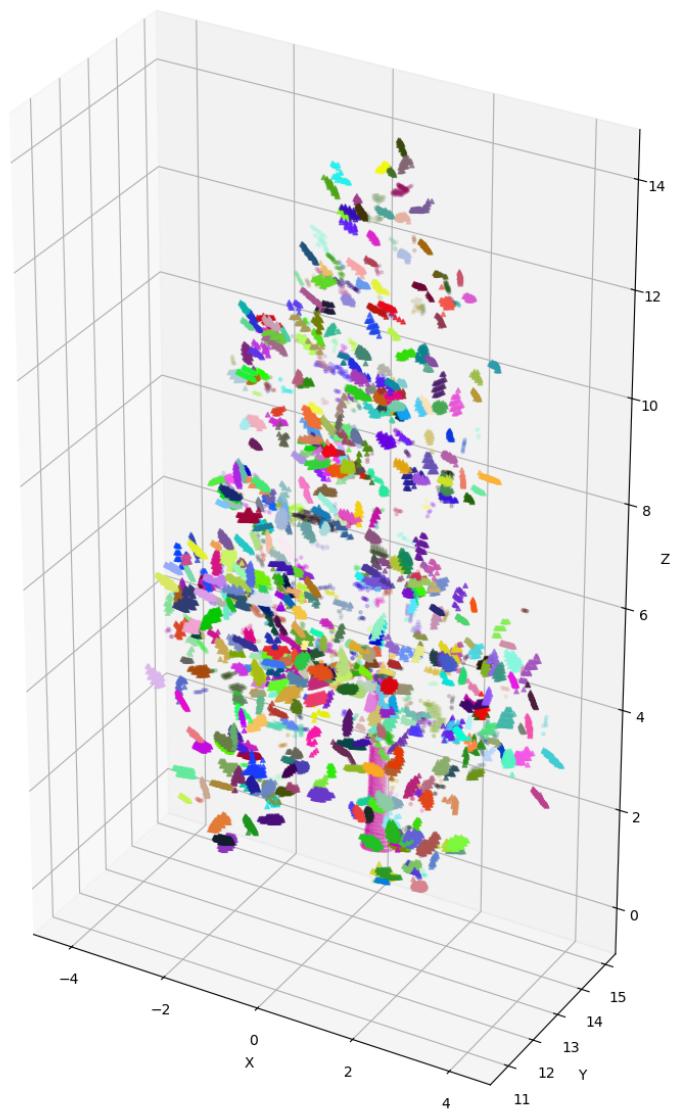
non_leaf_indices = ~leaf_indices
ax.scatter(sampled_points_plot[non_leaf_indices,0],\
sampled_points_plot[non_leaf_indices,1],\
sampled_points_plot[non_leaf_indices,2], c=colors_plot[non_leaf_indices],\
s=5, alpha=0.2)

ax.scatter(sampled_points_plot[leaf_indices,0],\
sampled_points_plot[leaf_indices,1], sampled_points_plot[leaf_indices,2],\
c=colors_plot[leaf_indices], s=10, marker='^', alpha=0.7)

ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_zlabel('Z')
ax.set_box_aspect([4, 2, 7]) # different aspect ratio
plt.tight_layout()

plt.show()

```



8.1 CT scan along z-axis, excluding spuriously large leaves

```
[42]: # plot ct scan along Z axis after removing large leaves
z_min = np.min(orig_points[:,2])
z_max = np.max(orig_points[:,2])
slice_thickness = 0.30 / 0.3 # original thickness before scaling
z = z_min
while z < z_max:
    slice_points = orig_points[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_labels = new_labels[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_is_leaf = is_leaf_label[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_leaf_areas = leaf_areas_column[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]
    slice_largest_distances_column = leaf_largest_distances_column[(orig_points[:,2] >= z) & (orig_points[:,2] < z + slice_thickness)]

    # plot the slice with cluster colors
    fig = plt.figure(figsize=(12,15))
    ax = fig.add_subplot(111)
    slice_points_plot = slice_points
    slice_labels_plot = slice_labels
    slice_leaf_areas_plot = slice_leaf_areas
    slice_largest_distances_plot = slice_largest_distances_column

    colors_plot = np.array([label_to_color[label] for label in slice_labels_plot])
    # plot leaf points as triangles
    leaf_indices = slice_is_leaf & (slice_leaf_areas_plot < leaf_area_threshold) & (slice_largest_distances_plot < leaf_distance_threshold)
    non_leaf_indices = ~leaf_indices
    ax.scatter(slice_points_plot[non_leaf_indices,0], slice_points_plot[non_leaf_indices,1], c=colors_plot[non_leaf_indices], s=5, alpha=0.5)
    ax.scatter(slice_points_plot[leaf_indices,0], slice_points_plot[leaf_indices,1], c=colors_plot[leaf_indices], s=15, marker='^', alpha=0.7)

    # show cluster ids
    for label in set(slice_labels_plot):
        if label == -1:
            continue
        label_indices = slice_labels_plot == label
```

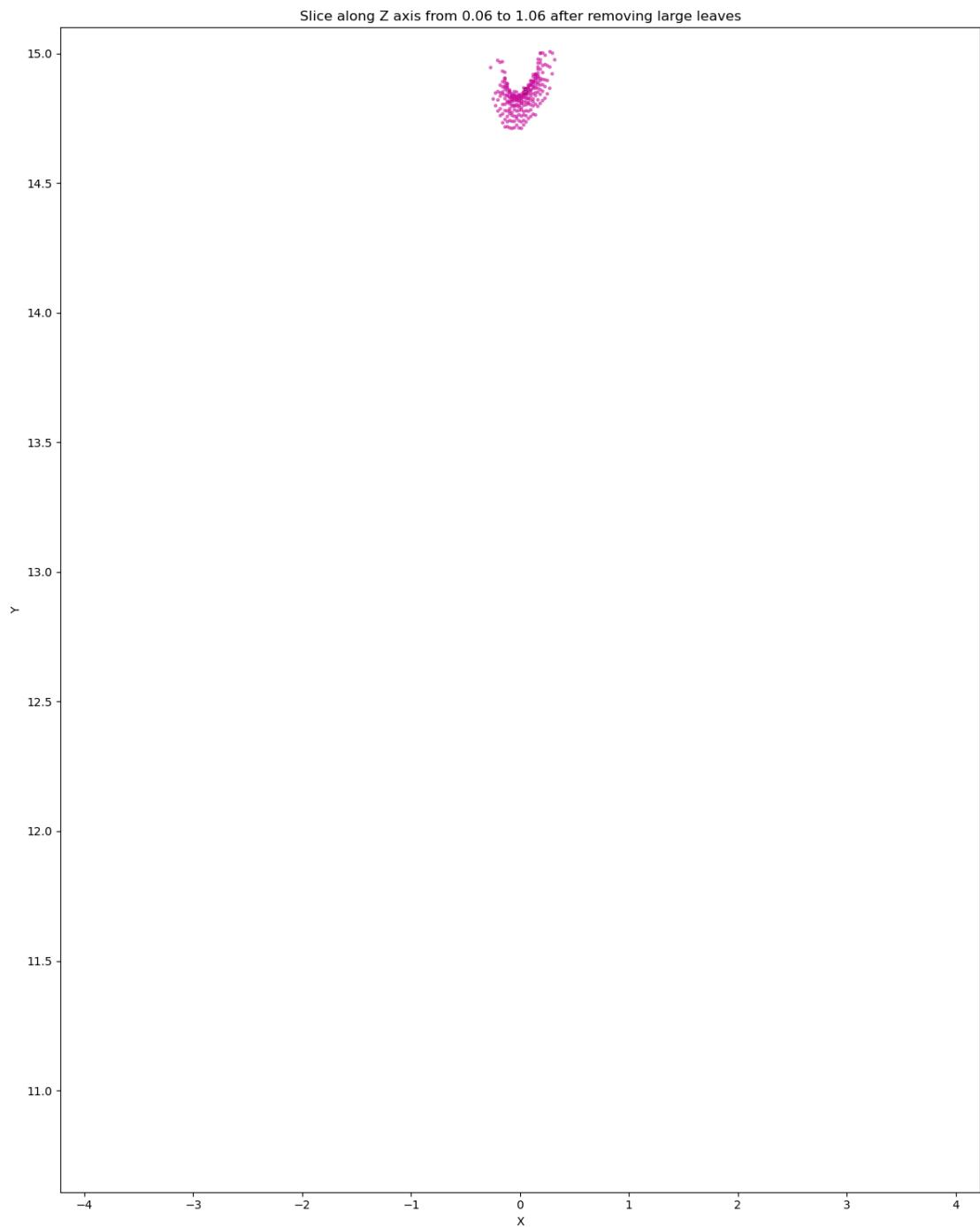
```

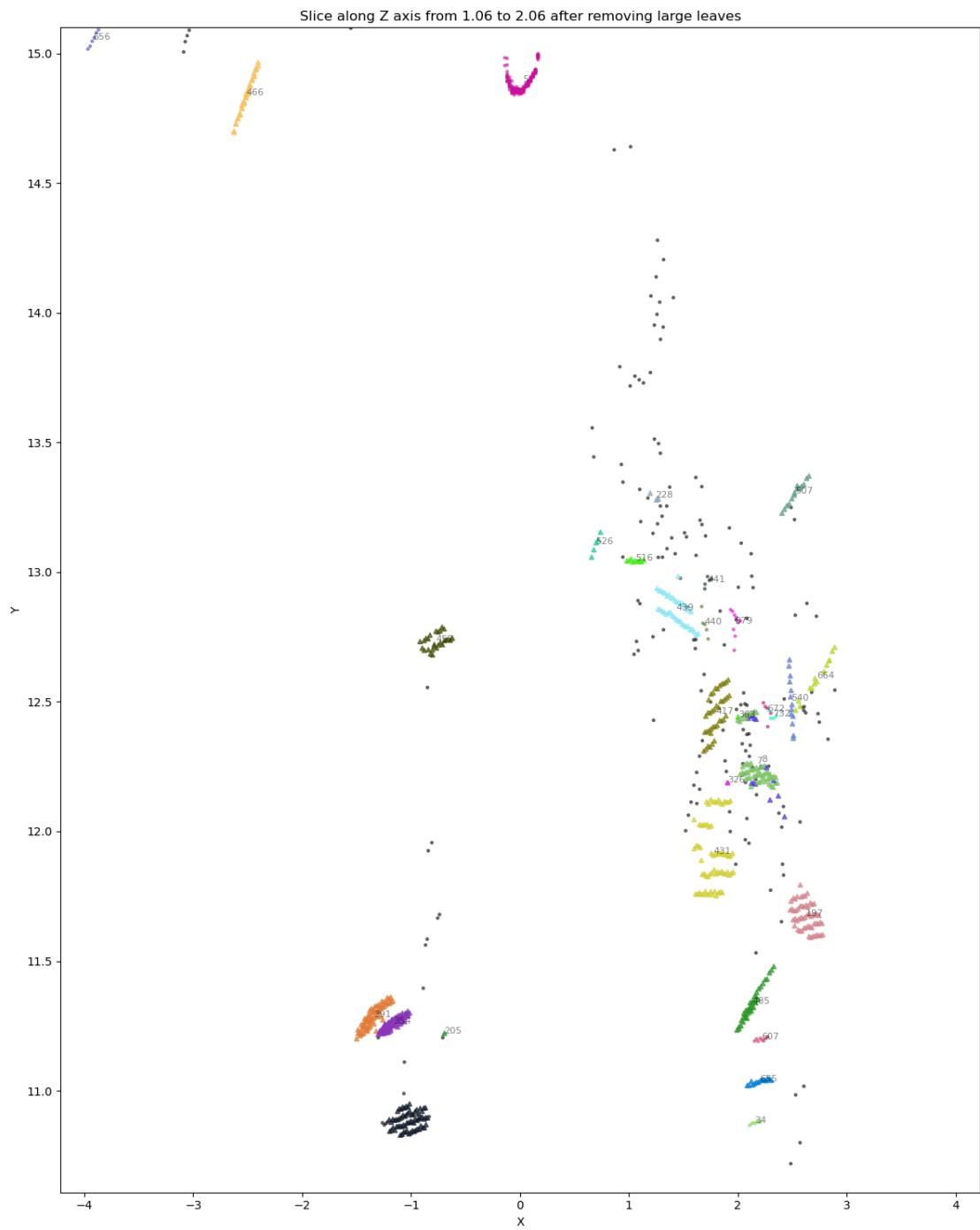
if np.sum(label_indices) == 0:
    continue
mean_x = np.mean(slice_points_plot[label_indices,0])
mean_y = np.mean(slice_points_plot[label_indices,1])
ax.text(mean_x, mean_y, str(label), color='black', fontsize=8, alpha=0.
↪5)

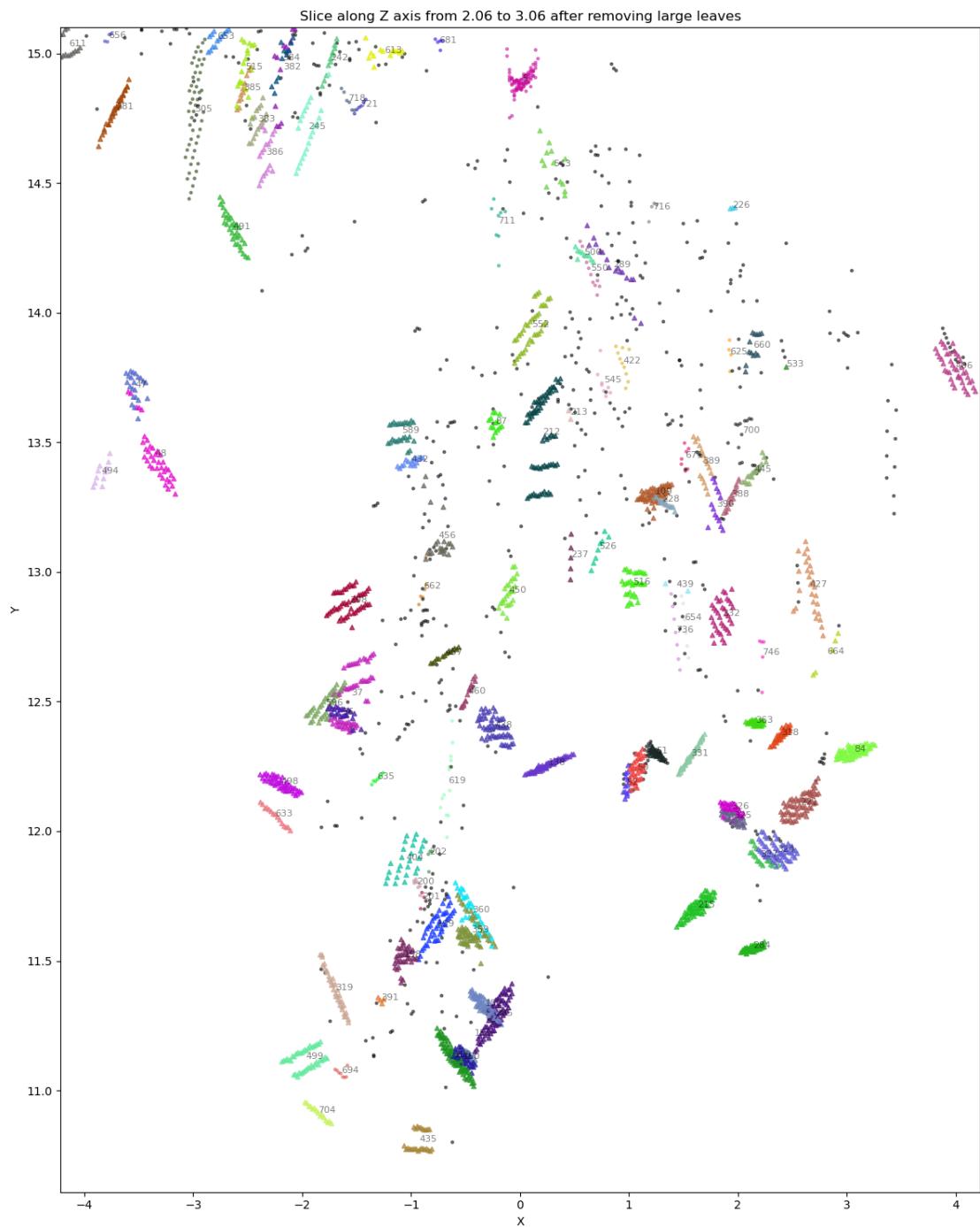
ax.set_xlabel('X')
ax.set_ylabel('Y')
# ax.set_aspect('equal', adjustable='box')
ax.set_xlim(np.min(orig_points[:,0]), np.max(orig_points[:,0]))
ax.set_ylim(np.min(orig_points[:,1]), np.max(orig_points[:,1]))
ax.set_title(f'Slice along Z axis from {z:.2f} to {z + slice_thickness:.2f} ↪
↪after removing large leaves')
plt.tight_layout()
plt.show()

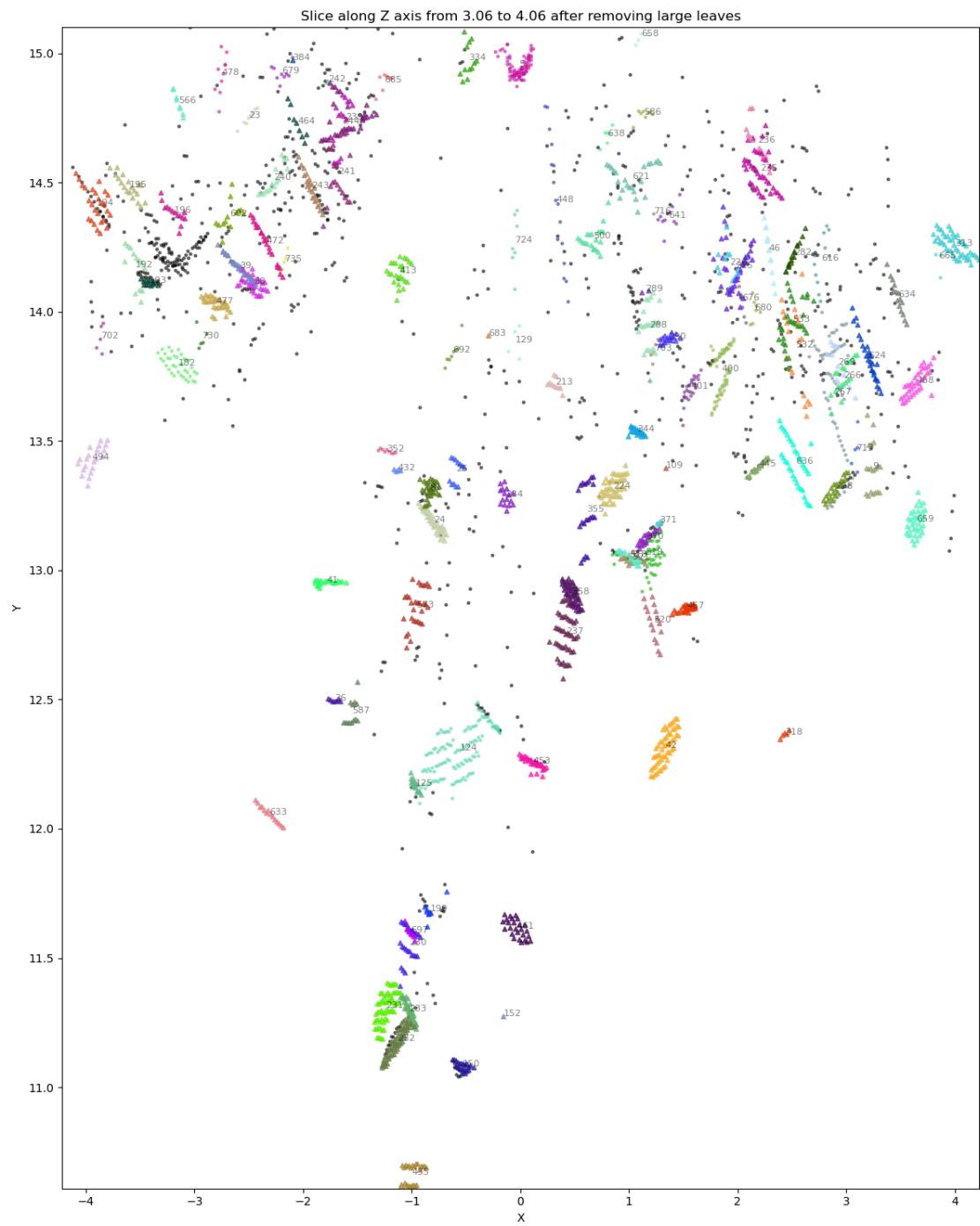
z += slice_thickness

```

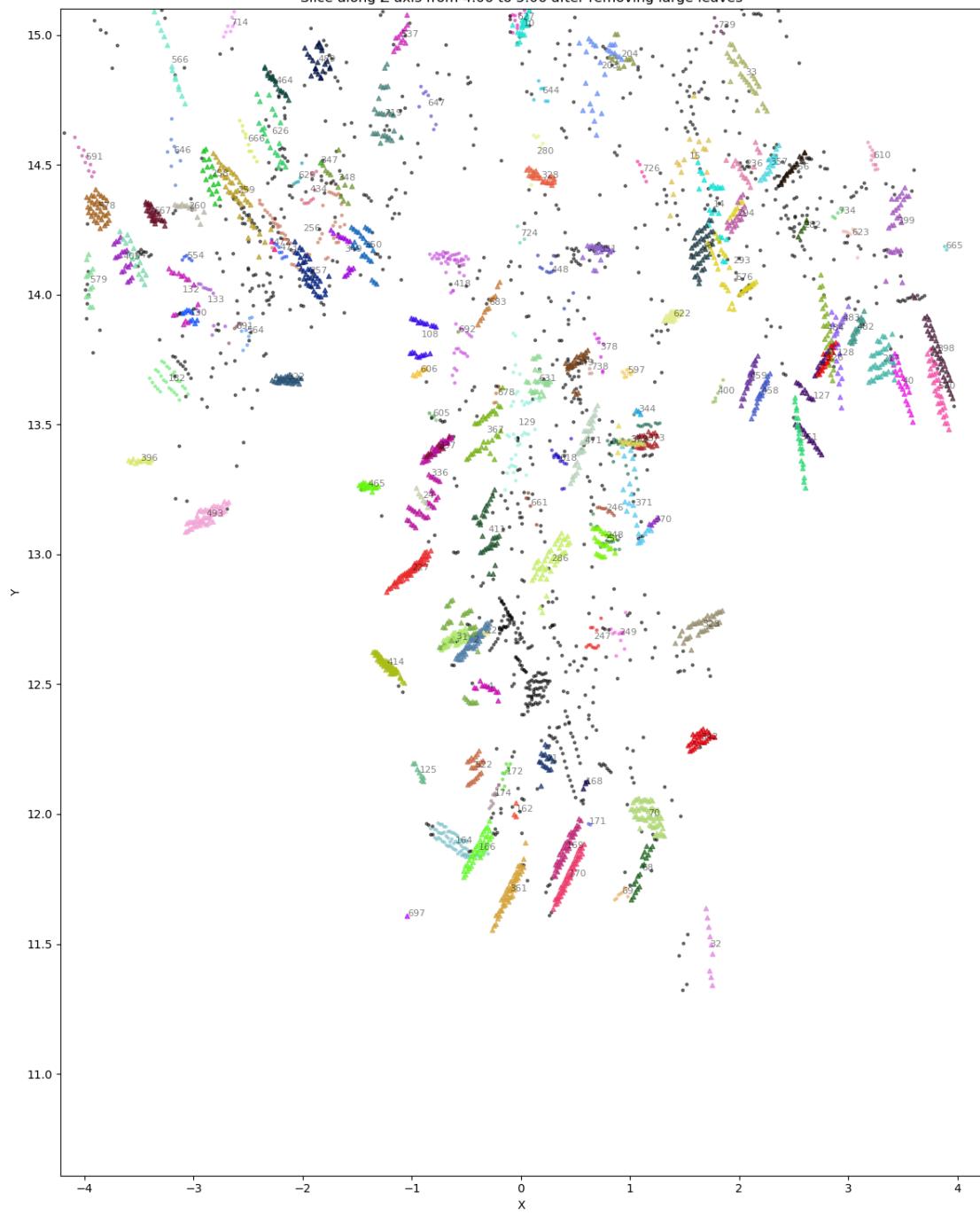


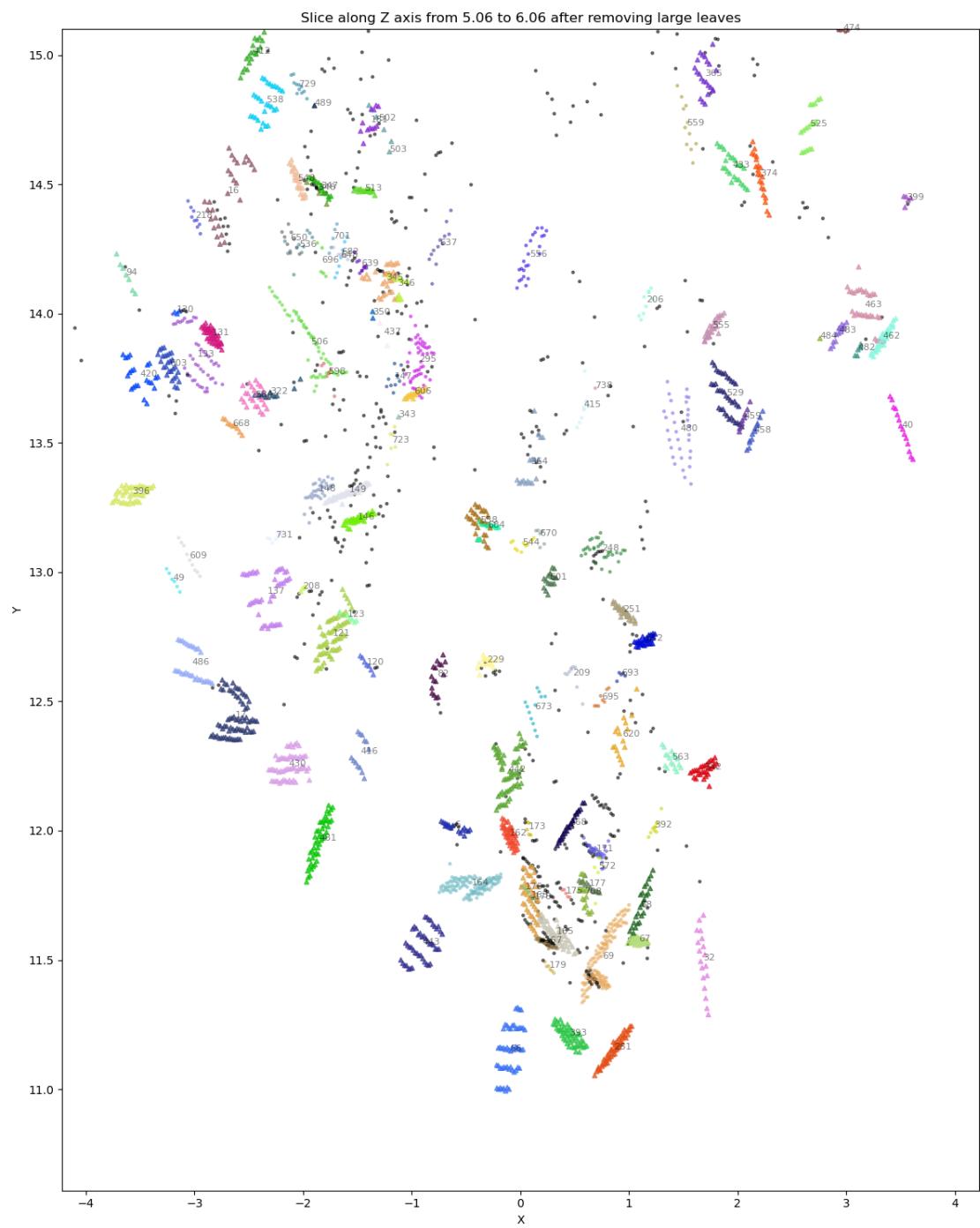


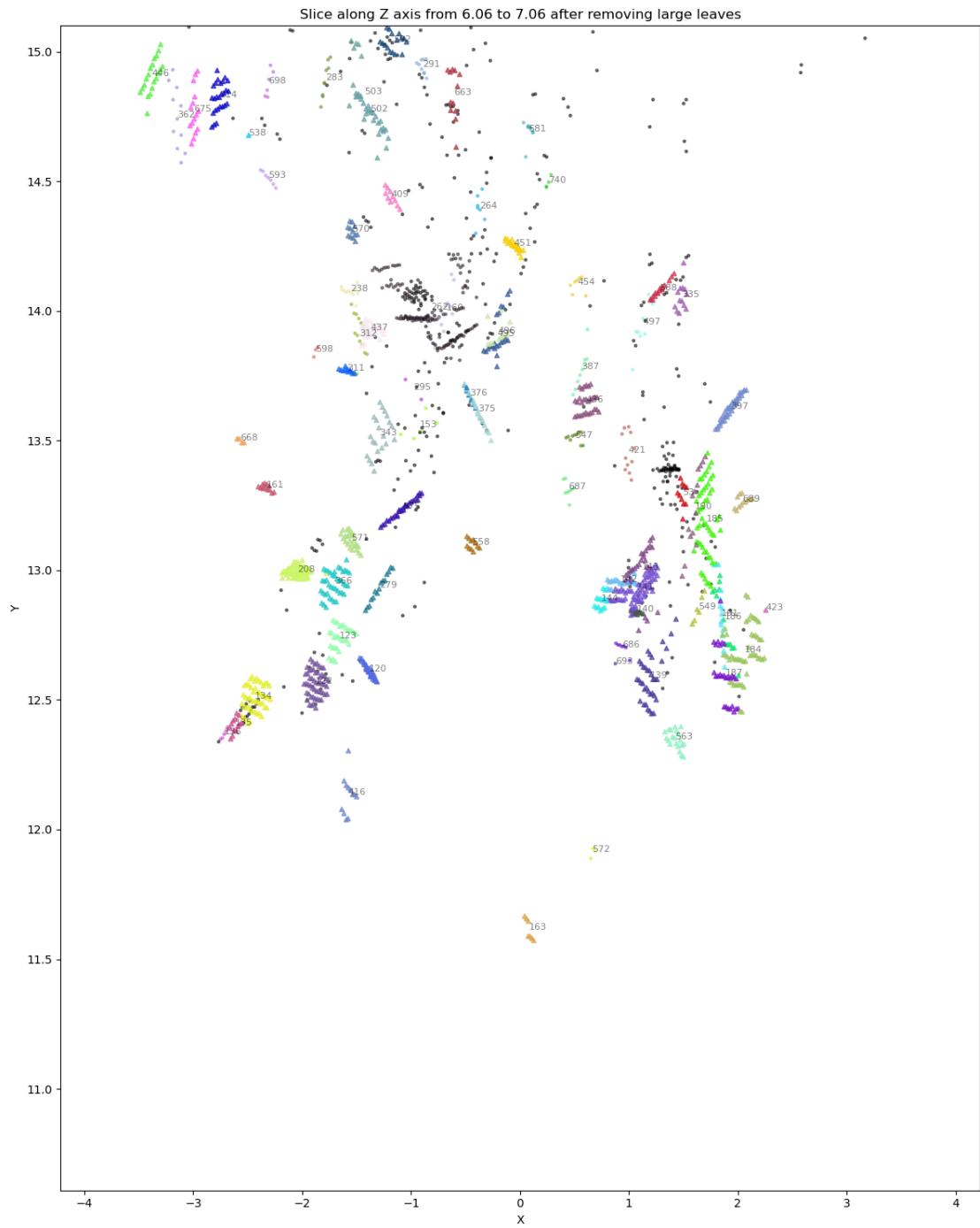


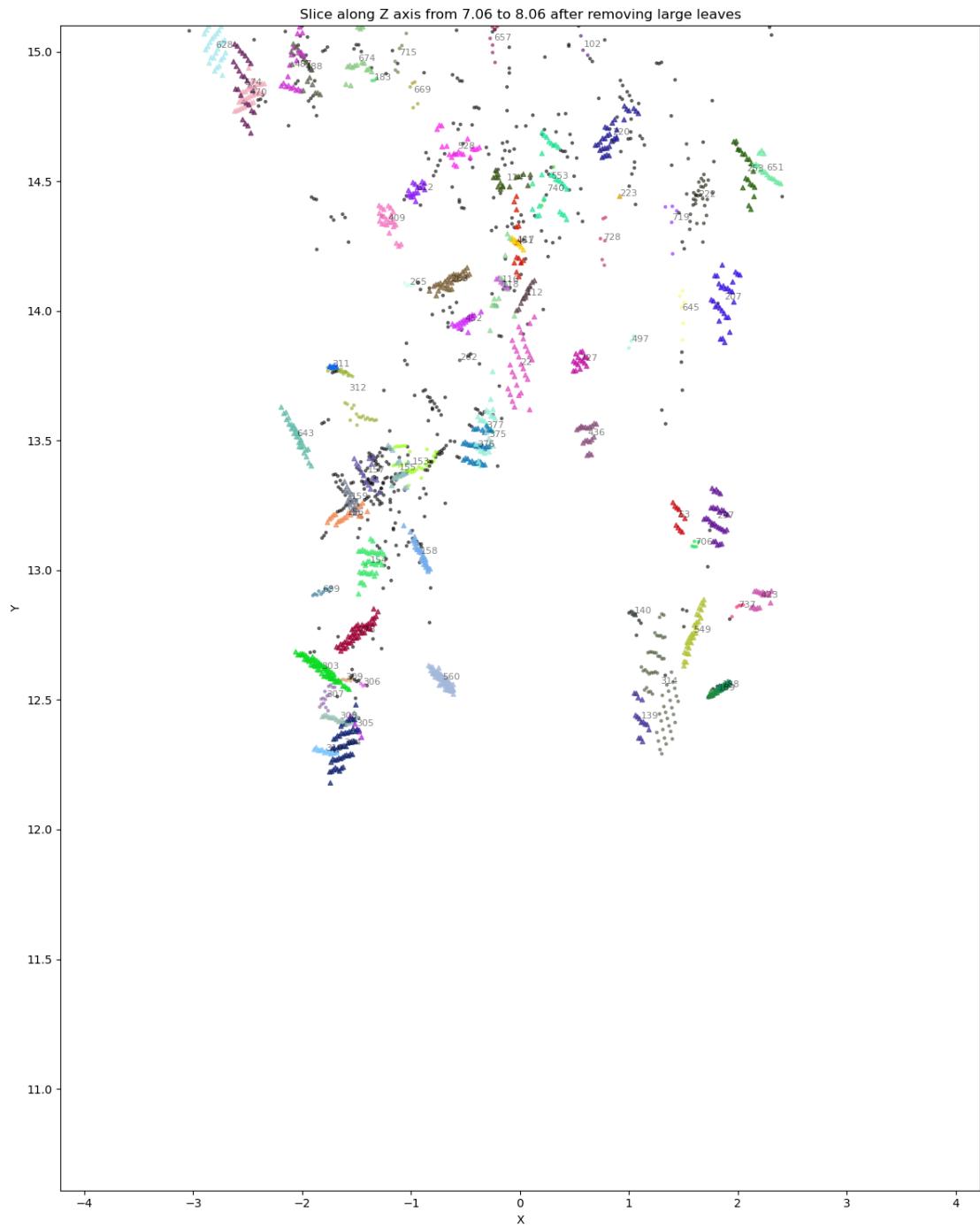


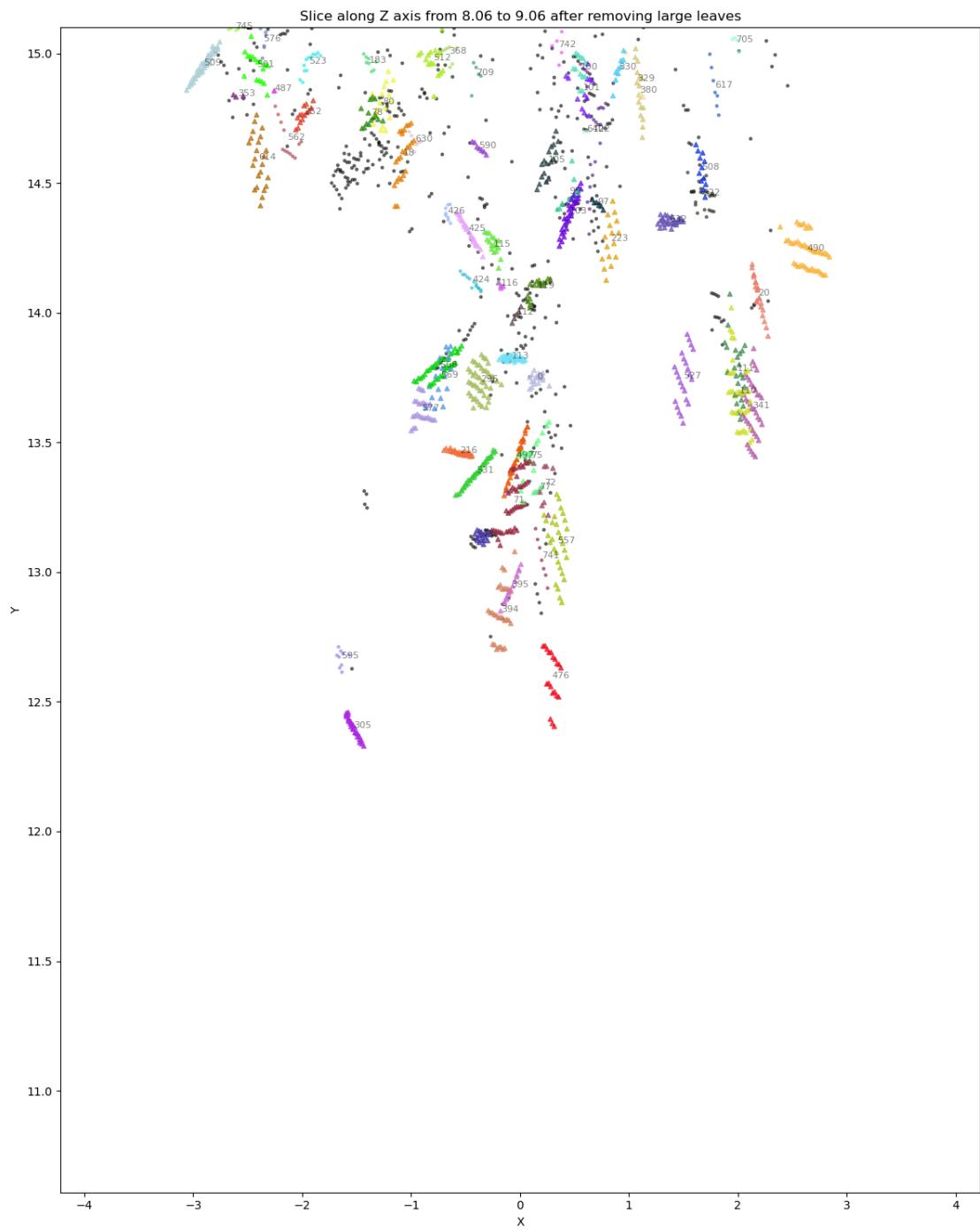
Slice along Z axis from 4.06 to 5.06 after removing large leaves

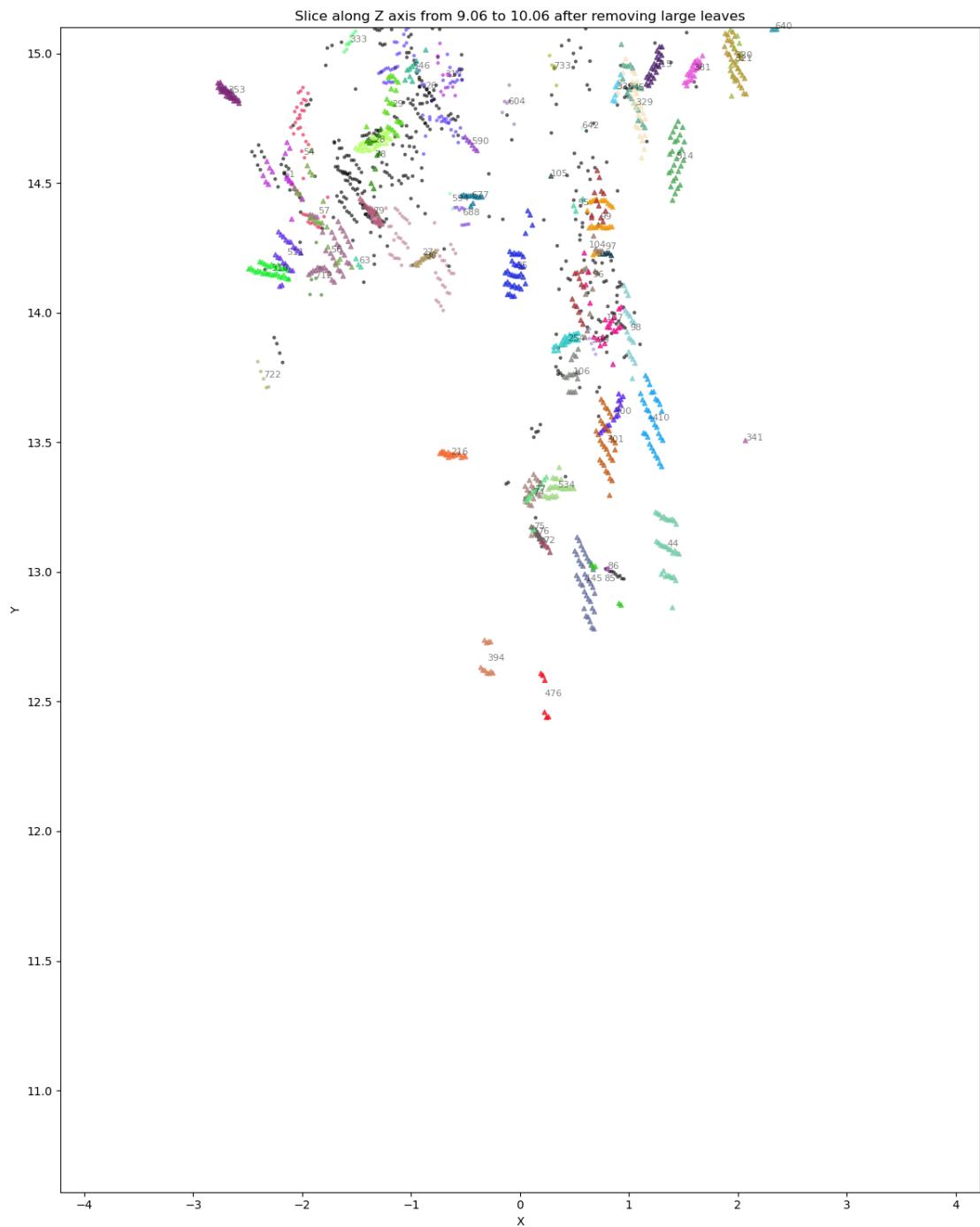


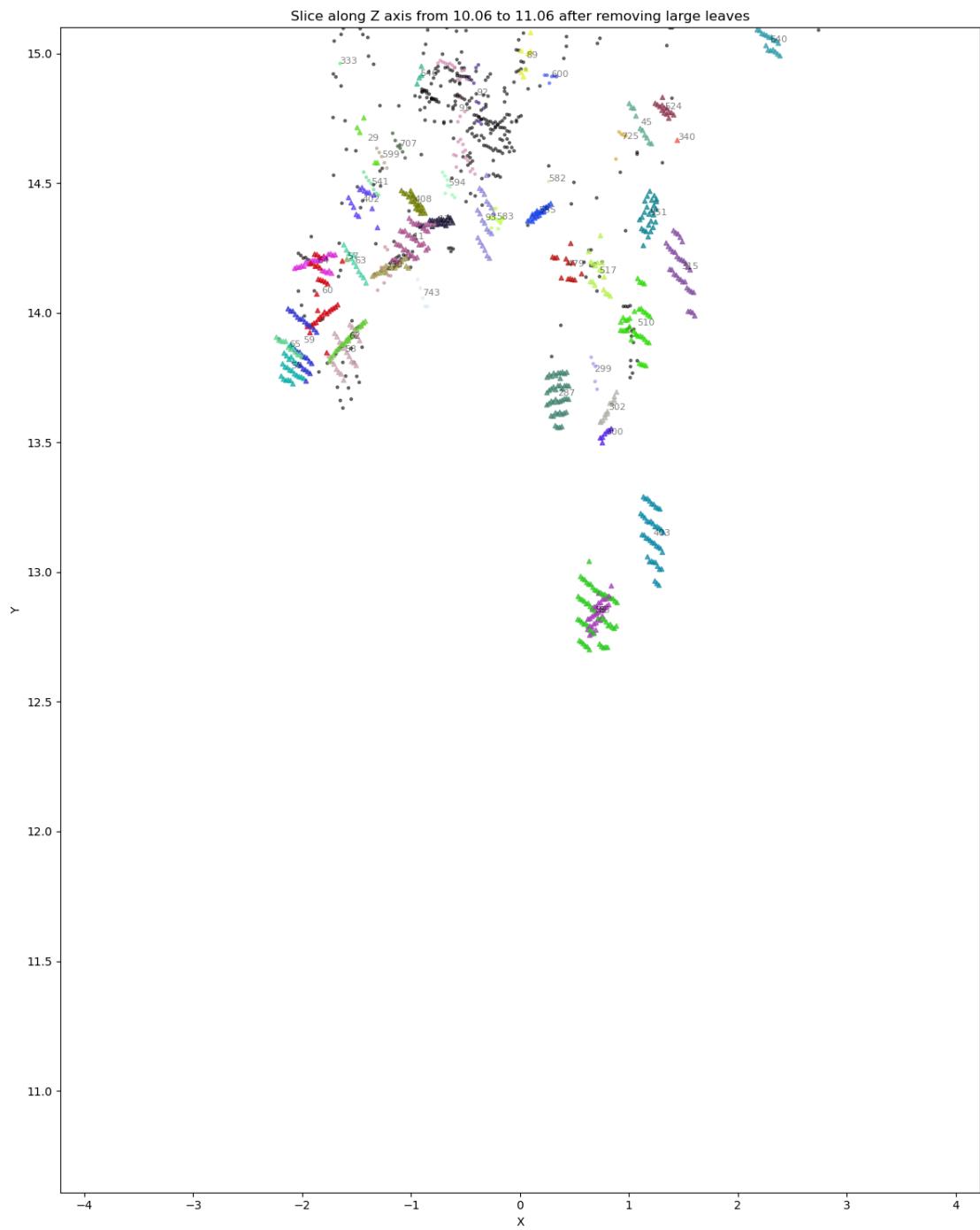


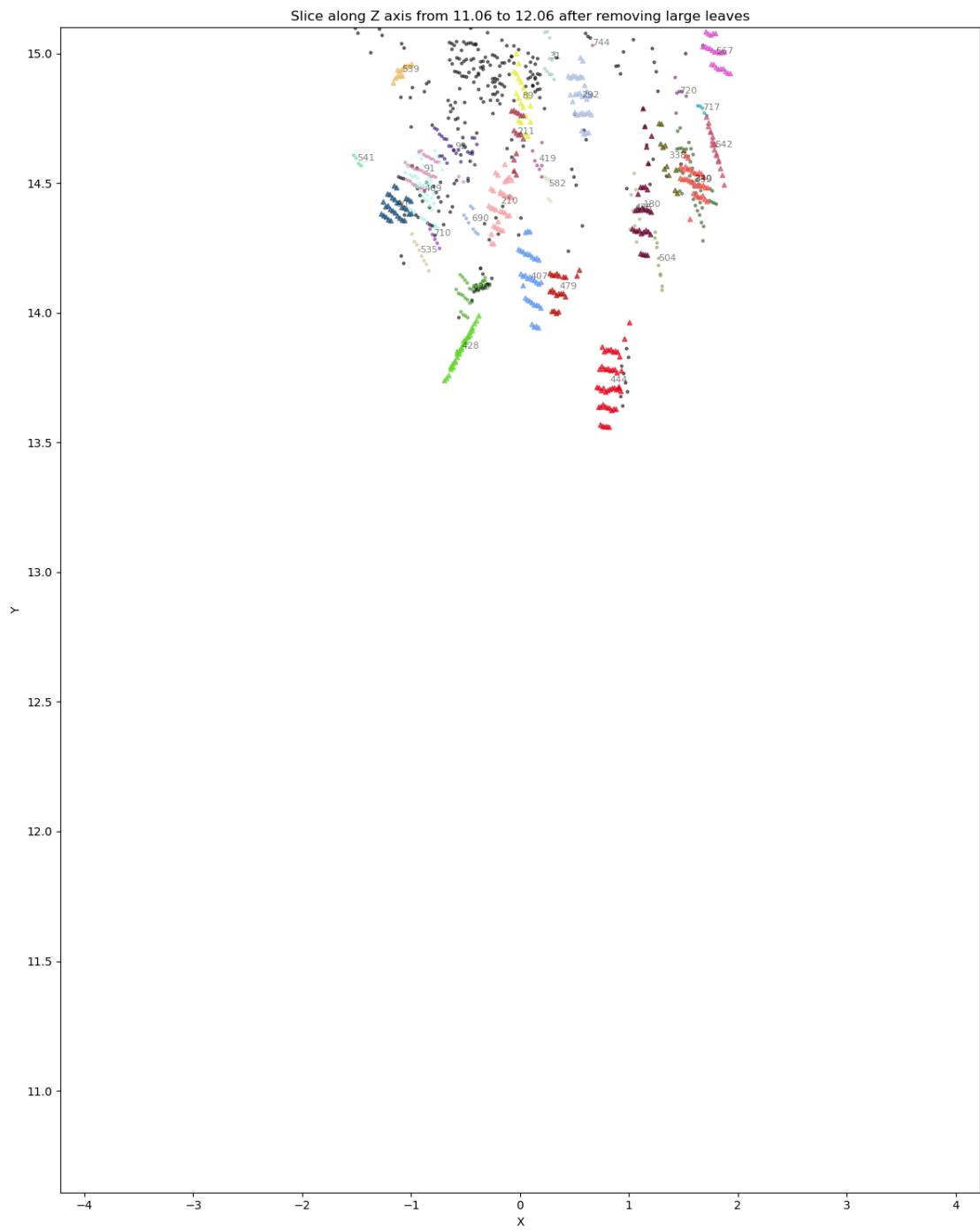


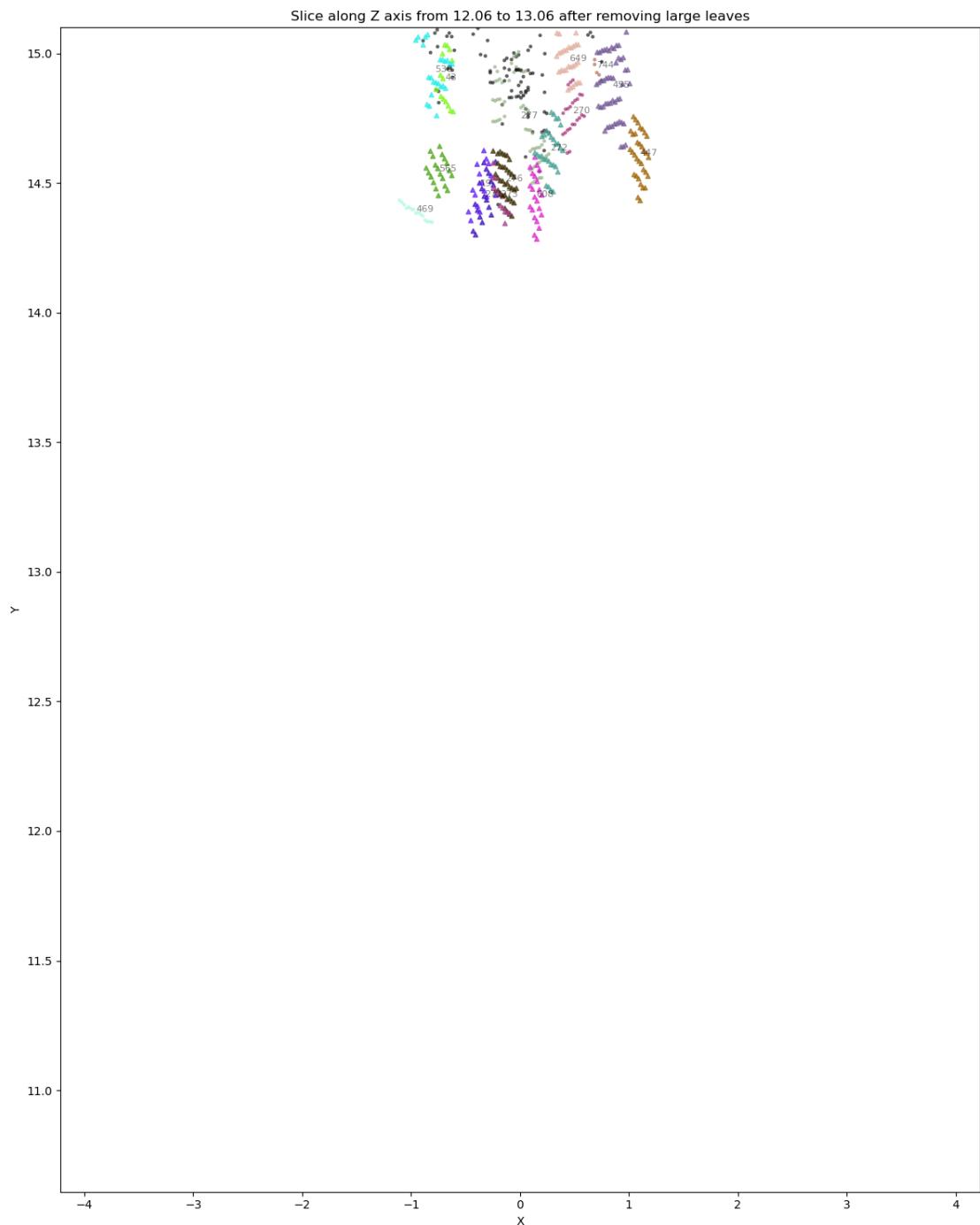


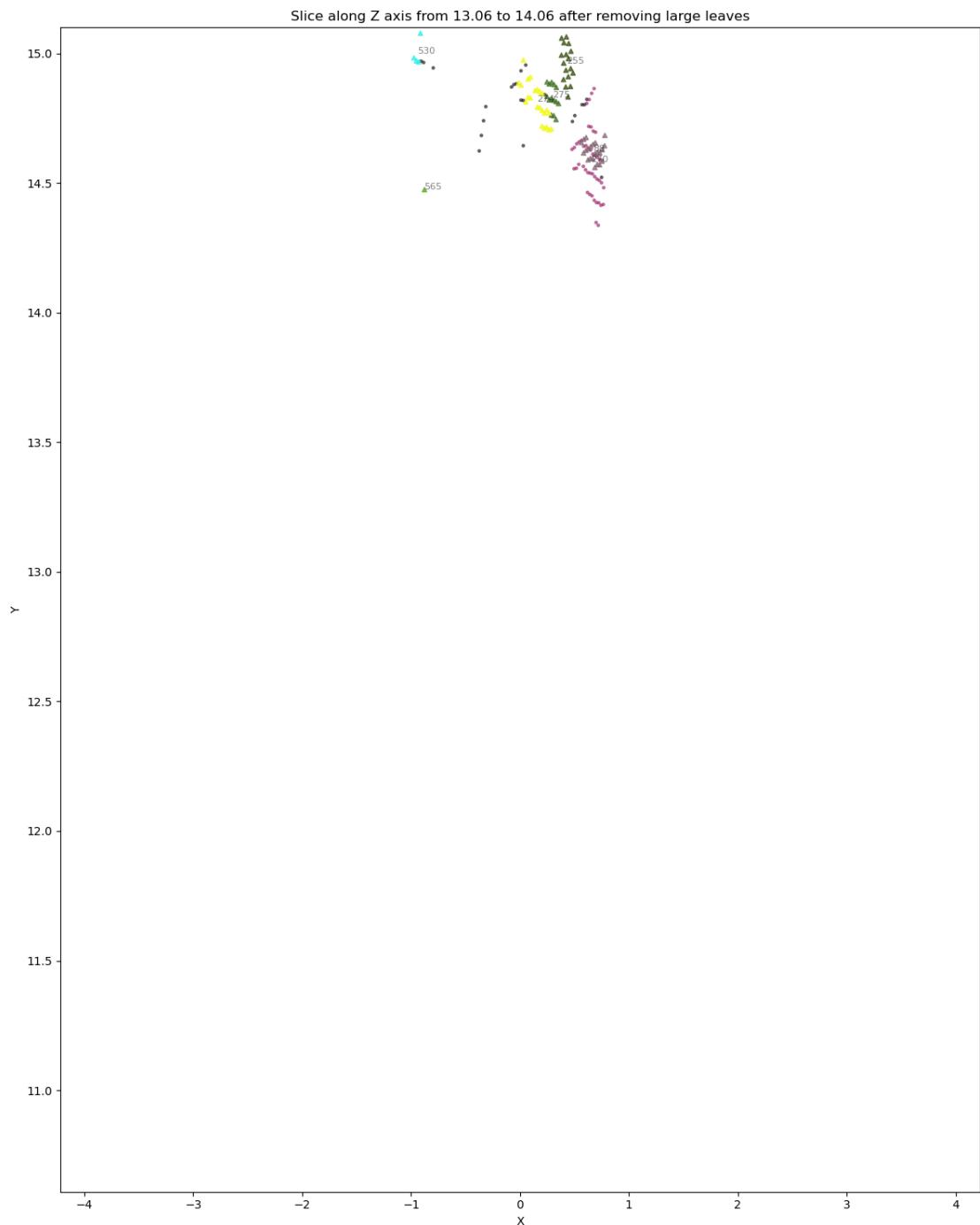












8.2 CT scan along y-axis, excluding spuriously large leaves

```
[43]: # ct scan along y axis after removing large leaves
y_min = np.min(orig_points[:,1])
y_max = np.max(orig_points[:,1])
slice_thickness = 0.4 / 0.5 # original thickness before scaling
y = y_min
while y < y_max:
    slice_points = orig_points[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]
    slice_labels = new_labels[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]
    slice_is_leaf = is_leaf_label[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]
    slice_leaf_areas = leaf_areas_column[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]
    slice_largest_distances_column = leaf_largest_distances_column[(orig_points[:,1] >= y) & (orig_points[:,1] < y + slice_thickness)]

    # plot the slice with cluster colors
    fig = plt.figure(figsize=(12,15))
    ax = fig.add_subplot(111)
    # valid_indices = slice_labels != -1
    # slice_points_plot = slice_points[valid_indices]
    # slice_labels_plot = slice_labels[valid_indices]

    slice_points_plot = slice_points
    slice_labels_plot = slice_labels

    # remove leaf points with area > threshold
    leaf_indices = slice_is_leaf & (slice_leaf_areas < leaf_area_threshold) &
                    (slice_largest_distances_column < leaf_distance_threshold)
    non_leaf_indices = ~leaf_indices

    colors_plot = np.array([label_to_color[label] for label in slice_labels_plot])
    # plot leaf points as triangles
    ax.scatter(slice_points_plot[non_leaf_indices,0], slice_points_plot[non_leaf_indices,2], c=colors_plot[non_leaf_indices], s=2, alpha=0.5)
    ax.scatter(slice_points_plot[leaf_indices,0], slice_points_plot[leaf_indices,2], c=colors_plot[leaf_indices], s=15, marker='^', alpha=0.7)
    # show cluster ids
    for label in set(slice_labels_plot):
```

```

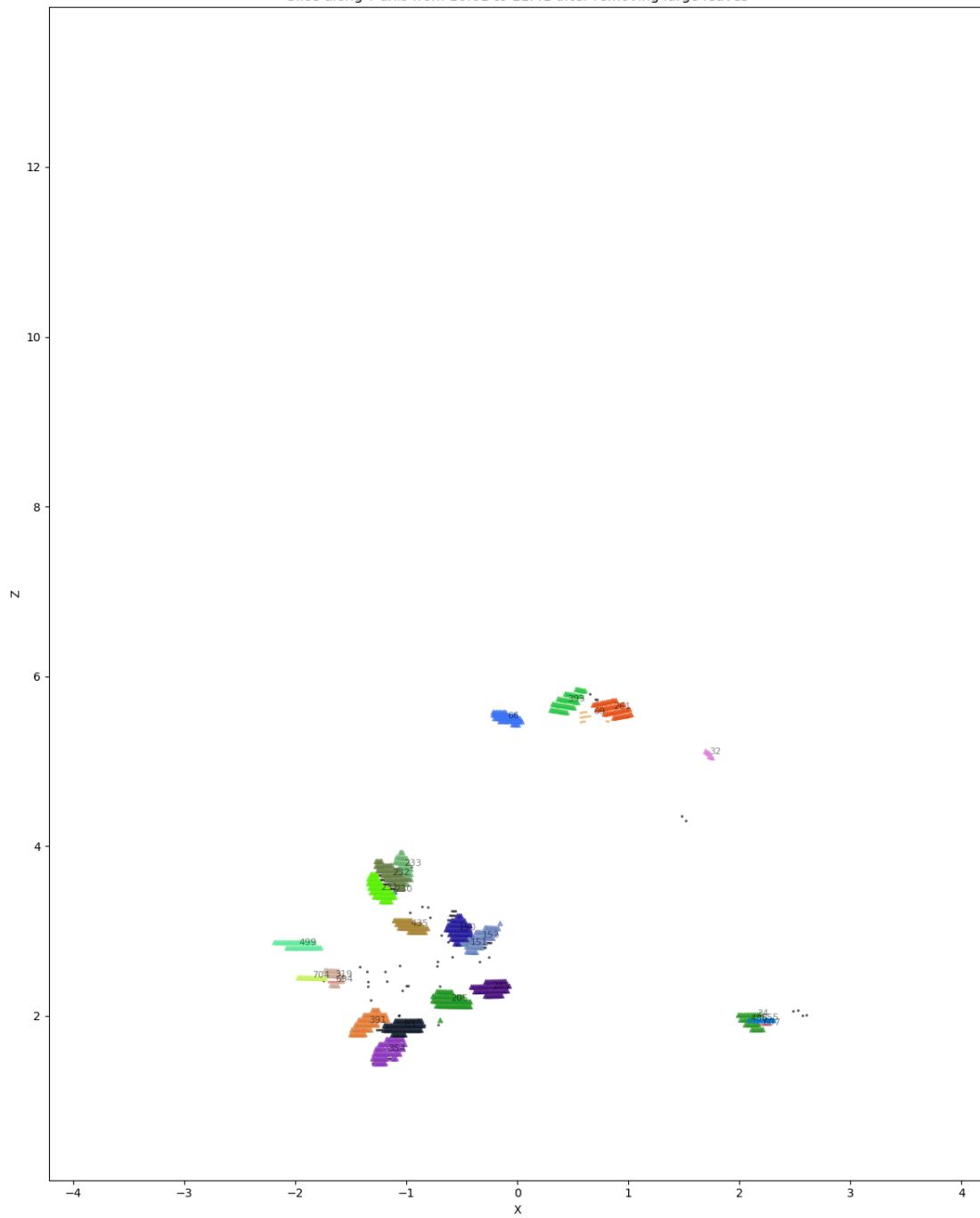
if label == -1:
    continue
label_indices = slice_labels_plot == label
if np.sum(label_indices) == 0:
    continue
mean_x = np.mean(slice_points_plot[label_indices,0])
mean_z = np.mean(slice_points_plot[label_indices,2])
ax.text(mean_x, mean_z, str(label), color='black', fontsize=8, alpha=0.
      ↵5)

ax.set_xlabel('X')
ax.set_ylabel('Z')
# ax.set_aspect('equal', adjustable='box')
ax.set_xlim(np.min(orig_points[:,0]), np.max(orig_points[:,0]))
ax.set_ylim(np.min(orig_points[:,2]), np.max(orig_points[:,2]))
ax.set_title(f'Slice along Y axis from {y:.2f} to {y + slice_thickness:.2f} ↵
      ↵after removing large leaves')
plt.tight_layout()
plt.show()

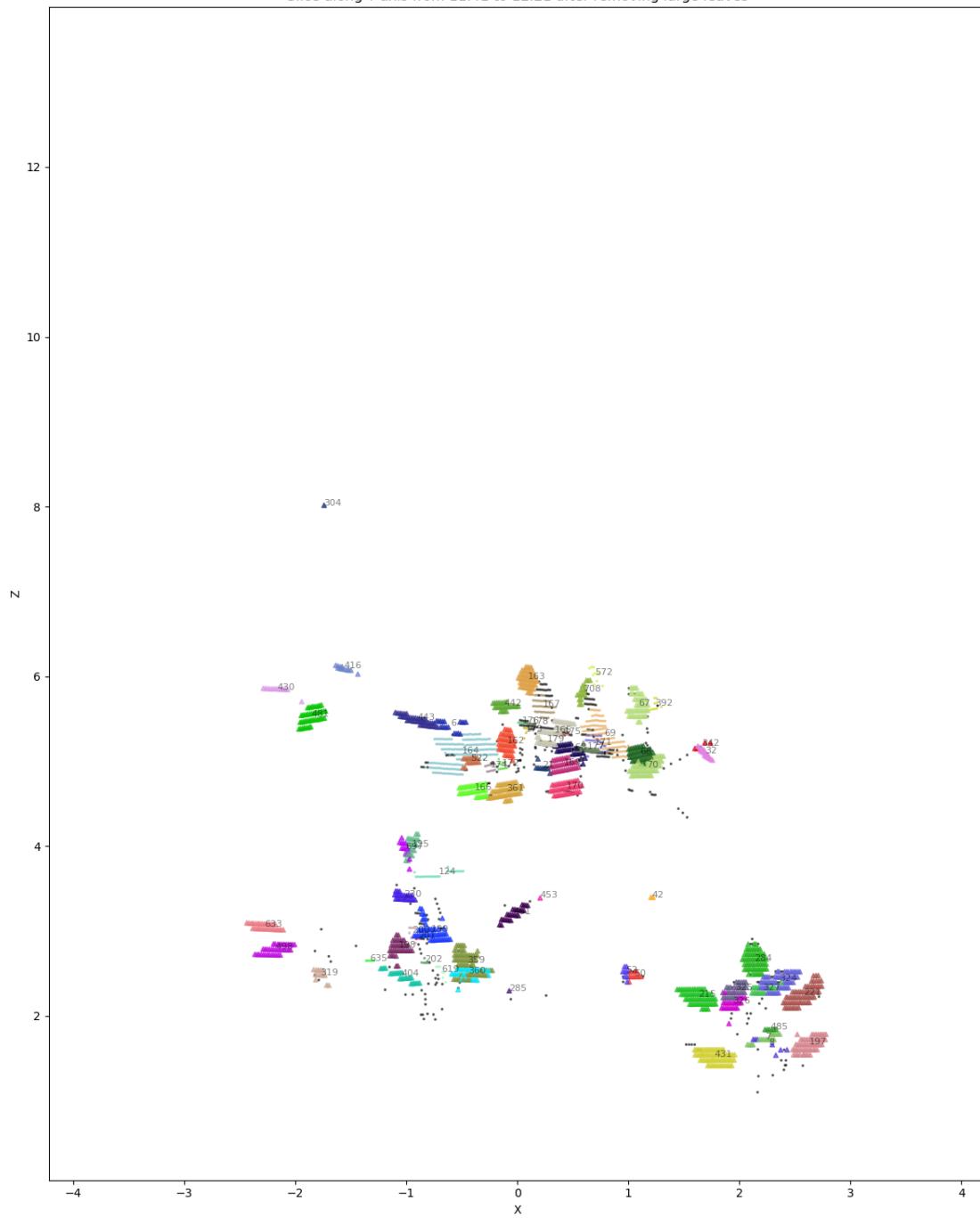
y += slice_thickness

```

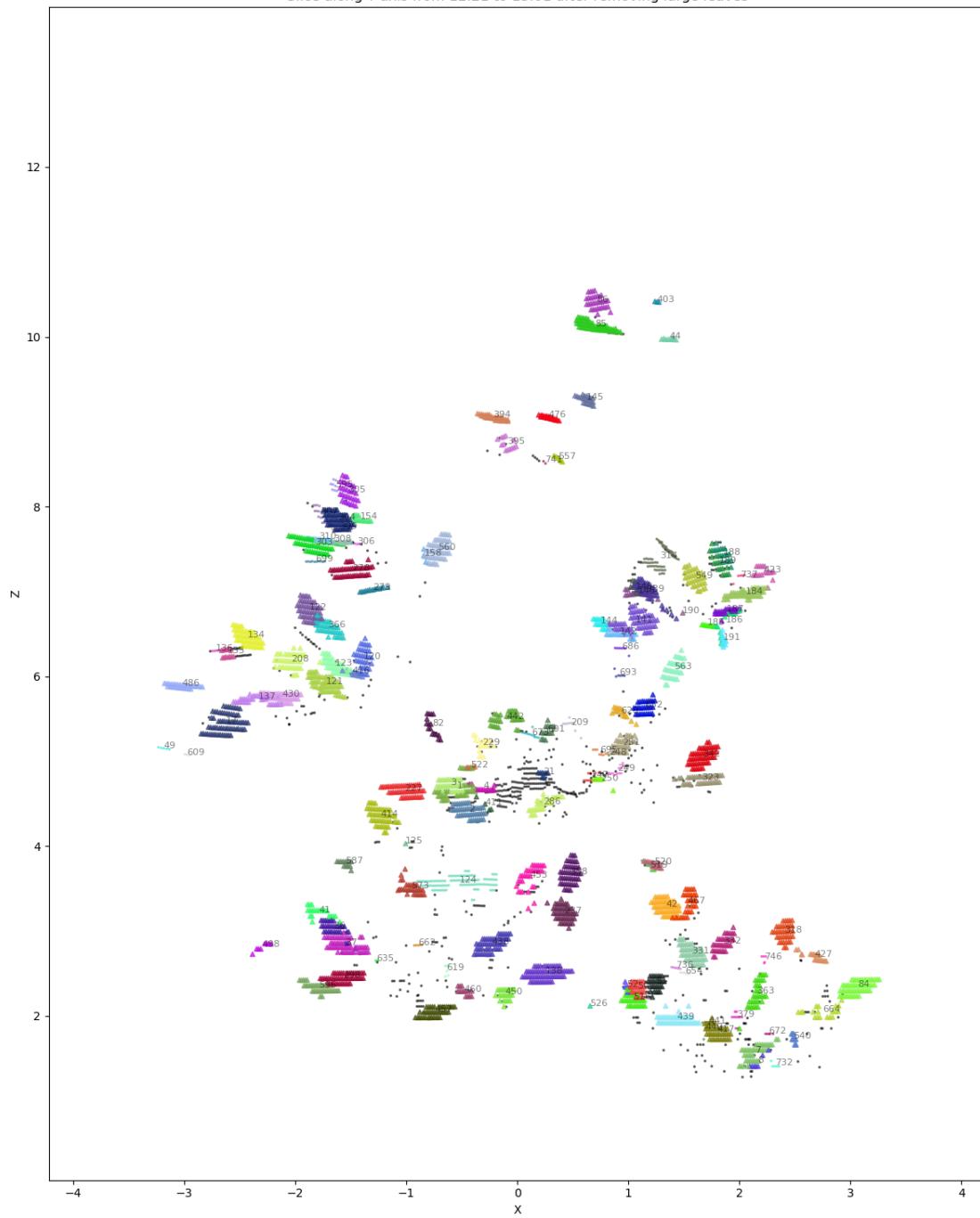
Slice along Y axis from 10.61 to 11.41 after removing large leaves



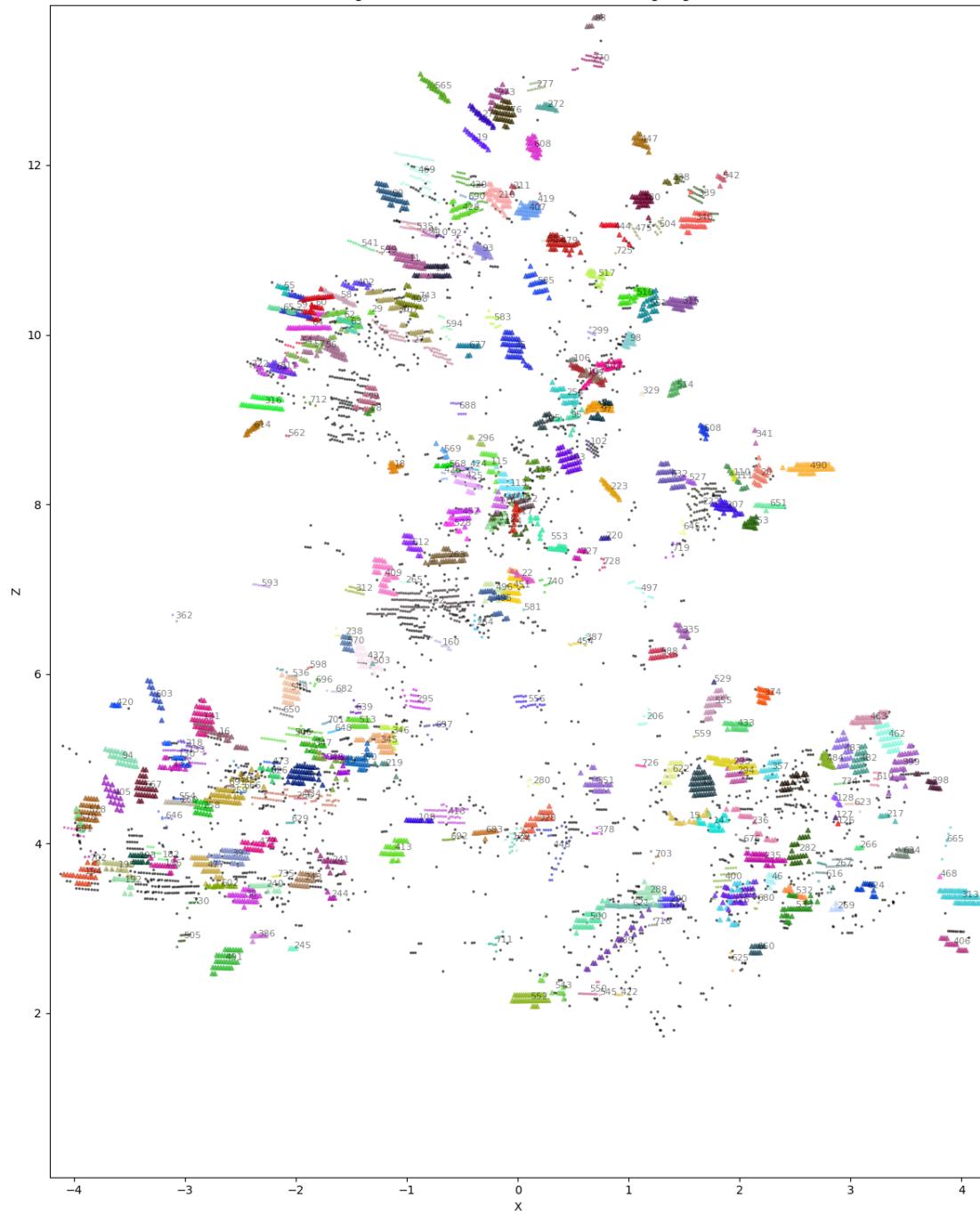
Slice along Y axis from 11.41 to 12.21 after removing large leaves

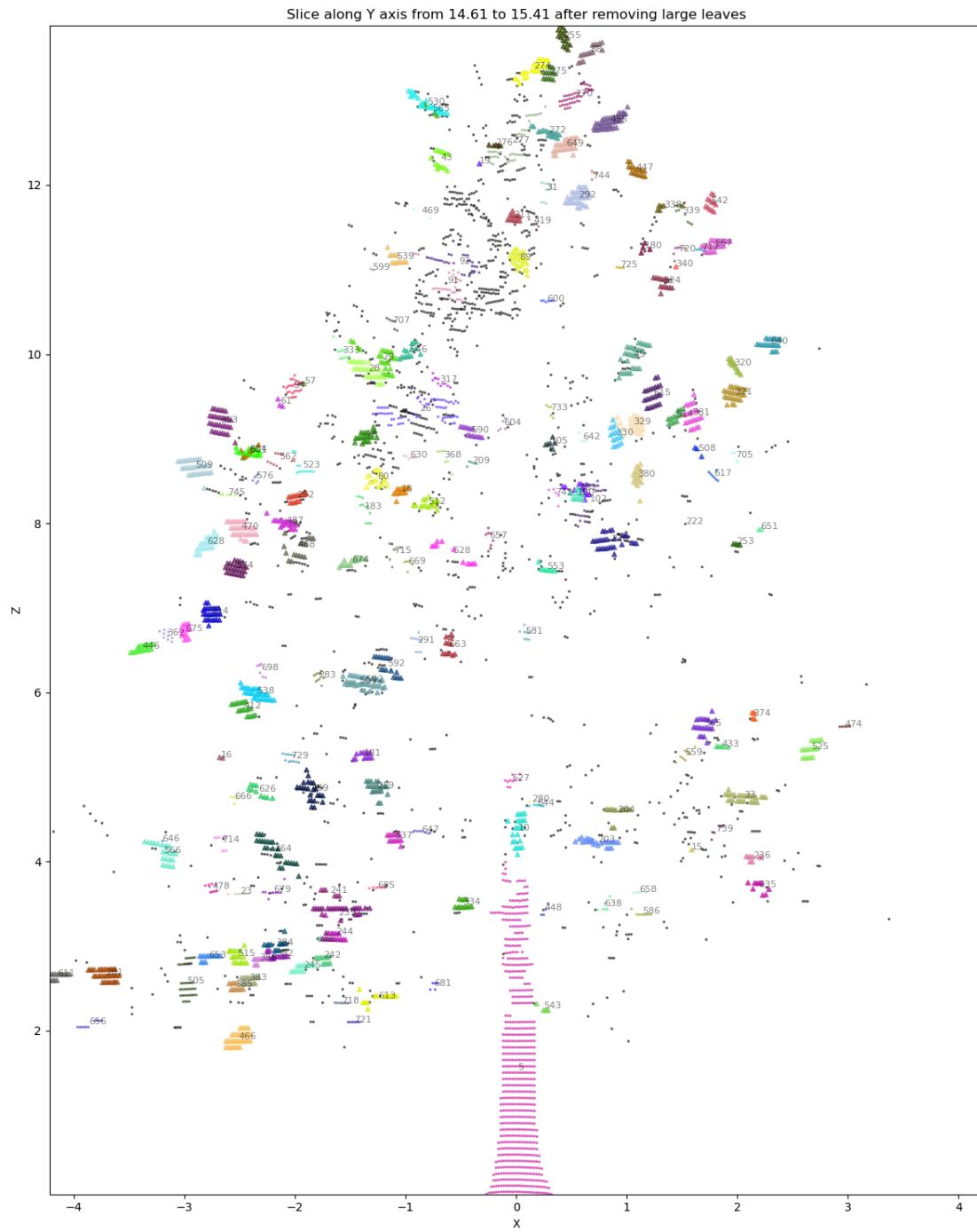


Slice along Y axis from 12.21 to 13.01 after removing large leaves



Slice along Y axis from 13.81 to 14.61 after removing large leaves





9 Summary

- We proposed a method to identify leaves from a tree point cloud obtained by a terrestrial LiDAR scanner.
- The method go through several steps:

1. Keep only the tree half which faces the LiDAR scanner.
2. Cluster the tree into smaller clusters.
3. For each smaller cluster, find the best clustering which gives the most leaf-like clusters.
The clustering proposing methods are: **DBSCAN with different scaling of y-axis and z-axis**; **RANSAC** plane fitting. The leaf-like clusters are identified by **shape analysis**.
4. We compute leaf area for each identified leaf cluster and sum them up to get the total leaf area. The leaves areas are approximated by half the **area of the convex hull** of the leaf clusters, because we assume the leaves are flat surfaces.
5. We only keep the leaves which have area below 0.15 m^2 to avoid suspiciously large leaves.
6. We visualize the final result and show CT scans along different axes, for qualitative evaluation.
7. We report the total leaf area as our estimation of leaf area of the tree.

10 Some drawbacks of our method

- If several leaves are very close to each other, such that they have high density at overlapping regions, they may be clustered as a single cluster by DBSCAN. In this case, our shape analysis may fail to identify them as leaf-like clusters. We have used RANSAC to separate such leaves, and successfully identified many leaves clusters this way. However, RANSAC does not respect the manifold structure of the point cloud, so in some cases, like the lower trunk region, where there are some nearly flat surfaces, the algorithm mistakenly identify these flat surfaces as leaves.
- We currently only identify a flat shape as leaf-like shape. However, some leaves may be curled or rolled, which may not be identified by our method. If we could identify a leaf-shape more specifically, the accuracy of leaf identification could be improved. (FAILED TO RECOGNIZE LEAF SHAPE)
- We did not solve the problem of occluded leaves. Some leaves may be partially occluded by other leaves or branches, leading to incomplete point clouds of these leaves. This may affect the shape analysis and leaf identification. Currently, we only identify the visible parts of these leaves. (FAILED TO HANDLE OCCLUSION)

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