Faculdade de Ciências da Universidade de Lisboa

Masters in Data Science

Data Visualization (2022/2023)

1st Project - Scientific Visualization using ParaView

Group VD 02

André Dias 59452, Cláudia Afonso 36273, Tiago Rodrigues 49593

20th of November 2022

Table of Contents

I. Introduction

The goal of this project is to use the open-source, multi-platform Paraview software to visualise the temporal evolution of data predicted by the research group eChanges (Ecology of Environmental Change) from the Faculty of Sciences of the University of Lisbon. As part of a research study, the regeneration rate of holm oaks growing on agriculturally abandoned lands was predicted over a period of 30 and 60 years in the absence of climate changes and over a period of 60 years in the presence of climate changes, considering the orography-based solar energy potential as a measure of the microclimatic conditions, among other factors [1]. The data was predicted for a terrain with a rectangular area containing 60 points along the x-axis (longitude) and 50 points along the y-axis (latitude), with each point georeferenced according to the Cartesian coordinates in the UTM WGS84 system and having its corresponding altitude value.

The information was provided in an excel file with six columns, where the first two contained the geographic location (in Cartesian coordinates) of the terrain, the third contained the altitude of the terrain at each point (scalar variable "Altitude"), the fourth and fifth contained the regeneration rate (scalar variable "Regen") following a period of 30 and 60 years without climate change, and finally, the sixth column contained the same variable following a period of 60 years in the presence of climate change.

To fulfil the goal of the project, the work was divided into the following main tasks: (1) data organisation in a file with the Visualization Toolkit (VTK) format, which includes the scalar variables "Altitude" and "Regen", as well as the newly created vector variable "RegenerationTrend" to indicate the growth trend over time, (2) creation of a series of pipelines in Paraview to represent the temporal evolution of the regeneration rate in the absence and presence of climate change, and finally, (3) correlation of the terrain areas with lower and higher regeneration rates to their orography-based potential solar radiation, considering their geographic location and altitude.

II. Data Organisation in the VTK file

To tackle this project, the first task consisted in structuring the data in a file with the VTK format, since this is the standard format required in the ParaView software. The VTK data file has two types of formats: Legacy (which can be divided into binary and ASCII) and XML. While XML allows for more flexibility, it is also more complex. Therefore, the chosen file format for this project was the Legacy ASCII format due to its simplicity and usage in the practical classes of this course. The information required to create a VTK file with this format is described in Figure 1. The title “Regeneration rates for holm oaks” was chosen as the dataset header.

Legacy format	**Component identifier**	**Created VTK datafile**
Version	1	# vtk DataFile Version 3.0
Header	2	Regeneration rates for holm oaks
Format	3	ASCII
Dataset structure	4	DATASET STRUCTURED_POINTS
Dataset attributes	5a	DIMENSIONS 60 50 3
	5b	ORIGIN 603995 4165513 0
	5c	SPACING 10 -10 200
	5d	POINT_DATA 9000 SCALAR Altitude float LOOKUP_TABLE default SCALAR Regen float LOOKUP_TABLE default VECTOR RegenerationTrend float

Figure 1 – Structure of the VTK file. The structure of a legacy VTK file consists of the following basic components: (1) file version identifier, (2) header, (3) file format, (4) dataset structure, and (5) dataset attributes, which include (5a) dimensions of the grid, (5b) origin values of the Cartesian coordinates, (5c) spacing between every point in the grid, and (5d) identification of the type of data structure (point or cell) that will be given a scalar or vector attribute.

Once the VTK file was created (“dados.vtk”), the data was introduced and organised in an appropriate structure that made it possible to create several sets of visualisations in Paraview. Since the coordinate points of the terrain form a regular grid, the suggestion of using the “STRUCTURED_POINTS” dataset structure was given for this project, in which both the geometry and the topology are regular. To see if this dataset structure is appropriate for the data, the excel file was first inspected. It was possible to see that the grid is composed of 60 points on the x-axis and 50 points on the y-axis evenly spaced between each other in both dimensions by a value of 10. Furthermore, it was possible to observe that 3000 points existed in the xy dimension, which implicitly means that the topology is regular as well. Therefore, the geometry and topology of the grid was confirmed to be in both cases regular and so a “STRUCTURED_POINTS” dataset structure is adequate to represent the data provided.

To generate a “STRUCTURED_POINTS” dataset structure, it is necessary to define the origin points and the spacing between them. Therefore, the origin was defined according to the coordinates of the first point of the grid using the parameter “ORIGIN 603995, 4165513, 0”, where “603995” is the first value for the variable longitude (x-axis), “4165513” is the first value for the variable latitude (y-axis) and “0” is the first value along the z-axis. The spacing between the grid points was set using the parameter “SPACING 10 -10 200”, where the first value represents the increment in value between each point along the x-axis, while the second value represents the decrement in value between each point along the y-axis. The z-axis was defined with a spacing value of 200, which corresponds to the distance between each of the three planes that will be created to study the regeneration rate of holm oaks as a function of time and climate change.

The topology was defined according to the dimensions and number of points of the grid. As previously mentioned, the grid is composed of 60 points along the x-axis and 50 points along the y-axis. Furthermore, the z-axis is defined by the three planes that will be created to study the regeneration rate of holm oaks as a function of time and climate change. Thus, the grid dimensions were defined by setting the “DIMENSIONS” parameter to “60 50 3”. Since each plane is composed of 3000 points and the three-dimensional grid has three planes, the number of points in the “POINT_DATA” parameter was set to 9000.

Two scalar variables associated with the terrain altitude and the regeneration rate of holm oaks, aptly named “Altitude” and “Regen”, were declared. A vector variable associated with the growth trend of the regeneration rate of holm oaks was also declared with the name “RegenerationTrend”. Additionally, for the scalar variables the transfer function, which maps data to colours, was set to default with the parameter “LOOKUP_TABLE default”.

The scalar variable “Altitude” was declared in the VTK file by using the parameter “SCALARS Altitude float”, as shown in Figure 2. This variable was defined as a float since the values associated with it have decimal places. For each of the three planes, the altitude values at each pair of x and y coordinates of the grid remain the same and do not change as a function of time or climate change. Thus, the 3000 values of altitude associated with each pair of x and y coordinates were introduced sequentially three times in the VTK file, which amounts to a total of 9000 points for this variable.

The second scalar variable “Regen” was subsequently declared in the VTK file, as shown in Figure 3. This variable was defined as a float since the values associated with it also have decimal places. Each of the three planes was defined with 3000 points associated with the Regen variable. The 3000 points in the first plane (z = 0) correspond to regeneration rate values over a time period of 30 years without climate change. The 3000 points in the second plane (z = 200) correspond to regeneration rate values over a time period of 60 years without climate change. Finally, the 3000 points in the third plane (z = 400) correspond to regeneration rate values over a time period of 60 years with climate change.

The last step in the VTK file creation process consisted in declaring the vector variable “RegenerationTrend”, which indicates in each point of the grid the growth trend of the “Regen” variable as a function of time and climate change. This vector variable was generated according to the project rules. As shown in Figure 4, in the first plane (z = 0) the 3000 vectors have along the x-axis the regeneration rate values over a period of 30 years without climate change, along the y-axis the regeneration rate values over a period of 60 years without climate change, and along the z-axis null values. In the second plane (z = 200), as shown in Figure 5, the 3000 vectors have null values along the three dimensions. In the third plane (z = 400), as shown in Figure 6, the 3000 vectors have along the x-axis the regeneration rate values over a period of 60 years with climate change, along the y-axis the regeneration rate values over a period of 60 years without climate change, and along the z-axis null values.

By combining all the above information, it was possible to structure the predicted data in a VTK file, which allowed the creation of a series of pipelines in Paraview to represent the evolution of the regeneration rate as a function of time and climate change.

Line		Line		Line	
10	SCALARS Altitude float				
11	LOOKUP_TABLE default				
12	157.445	3012	157.445	6012	157.445
13	158.255	3013	158.255	6013	158.255
14	158.769	3014	158.769	6014	158.769
15	159.023	3015	159.023	6015	159.023
16	159.149	3016	159.149	6016	159.149
17	159.229	3017	159.229	6017	159.229
18	159.301	3018	159.301	6018	159.301
19	159.386	3019	159.386	6019	159.386
20	159.491	3020	159.491	6020	159.491
21	159.618	3021	159.618	6021	159.618
22	159.75	3022	159.75	6022	159.75
23	159.803	3023	159.803	6023	159.803
24	159.841	3024	159.841	6024	159.841
25	159.891	3025	159.891	6025	159.891
26	160	3026	160	6026	160
27	160.088	3027	160.088	6027	160.088
28	160.113	3028	160.113	6028	160.113
29	160.119	3029	160.119	6029	160.119
30	160.247	3030	160.247	6030	160.247
31	160.219	3031	160.219	6031	160.219
32	160.167	3032	160.167	6032	160.167
33	160.131	3033	160.131	6033	160.131
34	159.999	3034	159.999	6034	159.999
35	159.765	3035	159.765	6035	159.765
36	159.551	3036	159.551	6036	159.551
...	...	...	...	...	...
	Scalar Altitude values for the 1^{st} plane		**Scalar Altitude values for the 2^{nd} plane**		**Scalar Altitude values for the 3^{rd} plane**

Figure 2 – Scalar "Altitude" variable declared in the VTK file. Values in the first, second and third planes correspond to the altitude scalar variable, which remains the same and does not change as a function of time or climate change.

Line		Line		Line	
9013	SCALARS Regen float				
9014	LOOKUP_TABLE default				
9015	56.0	12015	73.36	15015	52.8808
9016	48.0	12016	62.88	15016	45.3264
9017	48.0	12017	62.88	15017	45.3264
9018	48.0	12018	62.88	15018	45.3264
9019	48.0	12019	62.88	15019	45.3264
9020	57.0	12020	74.67	15020	53.8251
9021	57.0	12021	74.67	15021	53.8251
9022	57.0	12022	74.67	15022	53.8251
9023	63.0	12023	82.53	15023	59.4909
9024	63.0	12024	82.53	15024	59.4909
9025	63.0	12025	82.53	15025	59.4909
9026	63.0	12026	82.53	15026	59.4909
9027	68.0	12027	89.08	15027	64.2124
9028	68.0	12028	89.08	15028	64.2124
9029	68.0	12029	89.08	15029	64.2124
9030	68.0	12030	89.08	15030	64.2124
9031	68.0	12031	89.08	15031	64.2124
9032	68.0	12032	89.08	15032	64.2124
9033	68.0	12033	89.08	15033	64.2124
9034	68.0	12034	89.08	15034	64.2124
9035	68.0	12035	89.08	15035	64.2124
9036	68.0	12036	89.08	15036	64.2124
9037	68.0	12037	89.08	15037	64.2124
9038	68.0	12038	89.08	15038	64.2124
9039	68.0	12039	89.08	15039	64.2124
...	...	...	...	...	...
	Scalar Regen values for the 1^{st} plane (regeneration rate values over a period of 30 years without climate change)		**Scalar Regen values for the 2^{nd} plane (regeneration rate values over a period of 60 years without climate change)**		**Scalar Regen values for the 3^{rd} plane (regeneration rate values over a period of 60 years without climate change)**

Figure 3 – Scalar "Regen" variable declared in the VTK file. Values in the first plane correspond to the regeneration rate scalar variable over a period of 30 years without climate change; values in the second plane correspond to the regeneration rate scalar variable over a period of 60 years without climate change; values in the third plane correspond to the regeneration rate scalar variable over a period of 60 years with climate change.

Line			
18017	VECTORS	RegenerationTrend	float
18018	56.0	73.36	0
18019	48.0	62.88	0
18020	48.0	62.88	0
18021	48.0	62.88	0
18022	48.0	62.88	0
18023	57.0	74.67	0
18024	57.0	74.67	0
18025	57.0	74.67	0
18026	63.0	82.53	0
18027	63.0	82.53	0
18028	63.0	82.53	0
18029	63.0	82.53	0
18030	68.0	89.08	0
18031	68.0	89.08	0
18032	68.0	89.08	0
18033	68.0	89.08	0
18034	68.0	89.08	0
18035	68.0	89.08	0
18036	68.0	89.08	0
18037	68.0	89.08	0
18038	68.0	89.08	0
18039	68.0	89.08	0
18040	68.0	89.08	0
18041	68.0	89.08	0
18042	68.0	89.08	0
18018	56.0	73.36	0
…	…	…	…

Vectorial values along the x-axis of the 1st plane (regeneration rate values over a period of 30 years without climate change)

Vectorial values along the y-axis of the 1st plane (regeneration rate values over a period of 60 years without climate change)

Vectorial values along the z-axis of the 1st plane (null values)

Figure 4 – Values for the “RegenerationTrend” vector variable in the first plane declared in the VTK file. Values along the x-axis correspond to the regeneration rate scalar variable over a period of 30 years without climate change; values along the y-axis correspond to the regeneration rate scalar variable over a time period of 60 years without climate change; and values along the z-axis are null.

Line			
21018	0	0	0
21019	0	0	0
21020	0	0	0
21021	0	0	0
21022	0	0	0
21023	0	0	0
21024	0	0	0
21025	0	0	0
21026	0	0	0
21027	0	0	0
21028	0	0	0
21029	0	0	0
21030	0	0	0
21031	0	0	0
21032	0	0	0
21033	0	0	0
21034	0	0	0
21035	0	0	0
21036	0	0	0
21037	0	0	0
21038	0	0	0
21039	0	0	0
21040	0	0	0
21041	0	0	0
21042	0	0	0
21019	0	0	0
21020	0	0	0
…	…	…	…

Vectorial values along the x-axis of the 2nd plane (null values)

Vectorial values along the y-axis of the 2nd plane (null values)

Vectorial values along the z-axis of the 2nd plane (null values)

Figure 5 - Values for the “RegenerationTrend” vector variable in the second plane declared in the VTK file. Values along the x-axis, y-axis and z-axis are null.

Line	Vectorial values along the x-axis of the 3rd plane (regeneration rate over a period of 60 years with climate change)	Vectorial values along the y-axis of the 3rd plane (regeneration rate over a period of 60 years without climate change)	Vectorial values along the z-axis of the 3rd plane (null values)
24018	52.8808	73.36	0
24019	45.3264	62.88	0
24020	45.3264	62.88	0
24021	45.3264	62.88	0
24022	45.3264	62.88	0
24023	53.8251	74.67	0
24024	53.8251	74.67	0
24025	53.8251	74.67	0
24026	59.4909	82.53	0
24027	59.4909	82.53	0
24028	59.4909	82.53	0
24029	59.4909	82.53	0
24030	64.2124	89.08	0
24031	64.2124	89.08	0
24032	64.2124	89.08	0
24033	64.2124	89.08	0
24034	64.2124	89.08	0
24035	64.2124	89.08	0
24036	64.2124	89.08	0
24037	64.2124	89.08	0
24038	64.2124	89.08	0
24039	64.2124	89.08	0
24040	64.2124	89.08	0
24041	64.2124	89.08	0
24042	64.2124	89.08	0
…	…	…	…

Figure 6 – Values for the “RegenerationTrend” vector variable in the third plane declared in the VTK file. Values along the x-axis correspond to the regeneration rate scalar variable over a period of 60 years with climate change; values along the y-axis correspond to the regeneration rate scalar variable over a time period of 60 years without climate change; and values along the z-axis are null.

III. Data Visualization in the Paraview software

Representation of the different periods of regeneration with coloured cutting planes to analyse the evolution of the regeneration over time

After opening the VTK file using the Paraview software, the representation of the grid was changed to "Point Gaussian" to visualise the planes formed by all the points in the x, y and z dimensions. At this stage, three planes along the z-axis were observed, as shown in Figure 7. Each plane contains 3000 points associated with the scalar variables "Altitude" and "Regen" (regeneration rate) and with a vector variable "RegenerationTrend" that represents the regeneration rate growth trend. The first and second planes contain the data over a time period of 30 and 60 years, respectively, in the absence of climate change while the third plane contains data over a period of 60 years considering climate change effects.

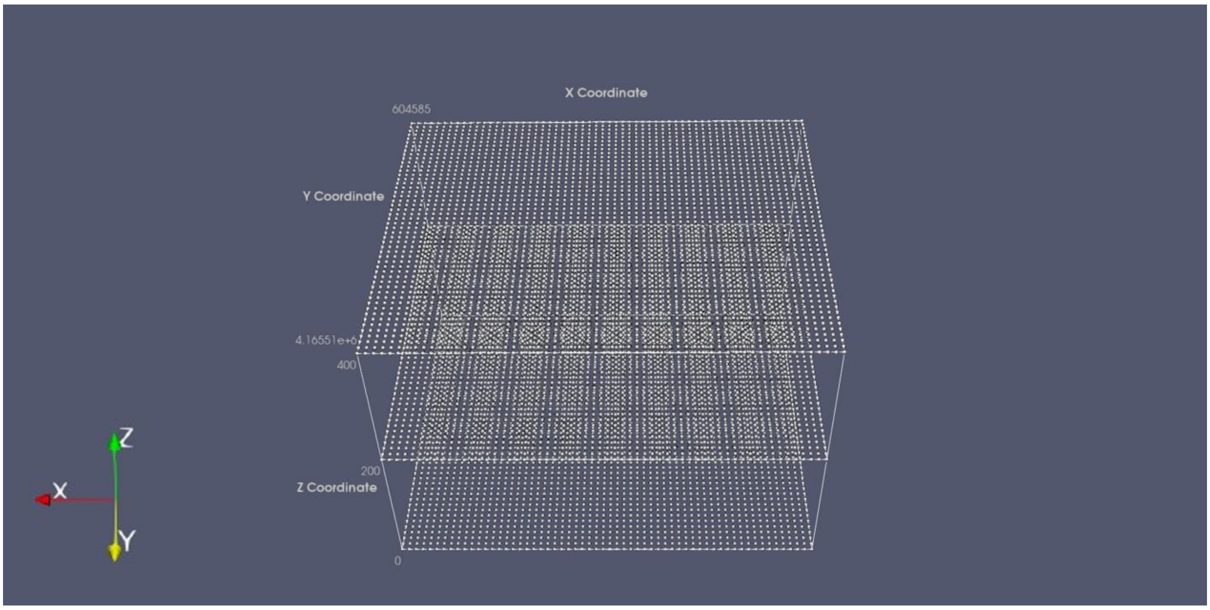

Figure 7 – Visualization of the three-dimensional grid using a "Point Gaussian" representation. Three different planes along the z-axis can be seen corresponding to the regeneration rate over a period of 30 years (bottom plane) and 60 years (mid plane) without the effects of climate change, and 60 years with the effects of climate change (top plane).

To visualise the scalar and vector quantities associated with each grid node, cutting planes were created. To accomplish this, the "Slice" filter was used and the normal vector in the "Plane Parameters" option was changed from (1,0,0) to (0,0,1) to create an orthogonal plane with respect to the z-axis, as shown in Figure 8. By setting the x and y coordinates to the origin values (603995, 4165513) and sequentially varying the value of the z coordinate according to the spacing value defined in the VTK file (0, 200, 400), three cutting planes were created, as shown in Figure 9. Surprisingly, when using the value of 0 for Z in the first plane, a cutting plane was not generated. However, this was overcome by setting Z equal to 0.001.

Each plane was coloured using a custom colour palette, where the high values of regeneration rate correspond to dark green and lower values to light beige, passing through light green for intermediate values. This representation is intuitive because forested areas are naturally associated with green and arid areas with beige.

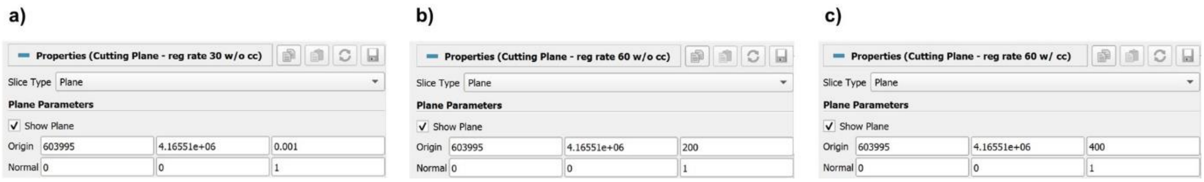

Figure 8 – Slicing parameters used to define the three cutting planes. a) In the bottom plane the Z was set to 0.001. b) In the middle plane the Z was set to 200; c) In the top plane the Z was set to 400.

As seen from the three cutting planes in Figure 9, there is a clear increase in the regeneration rate over time from 30 to 60 years (9b and 9c, respectively) when not considering the potential effects of climate change, because green areas got larger and darker while beige-coloured areas became smaller. It was also possible to visualise a decrease in the regeneration rate when the effects of climate change over a time period of 60 years (9d) were evaluated, since green areas got smaller and lighter and beige-coloured areas became bigger, when compared to the same time period in the absence of climate changes (9c). Lastly, comparing the regeneration rate over a time period of 30 years without climate change (9b) and over a rate of 60 years with climate change (9d) it becomes apparent that the coloured surface of the two is extremely similar, alluring to the severe impact of climate change on the regeneration rate.

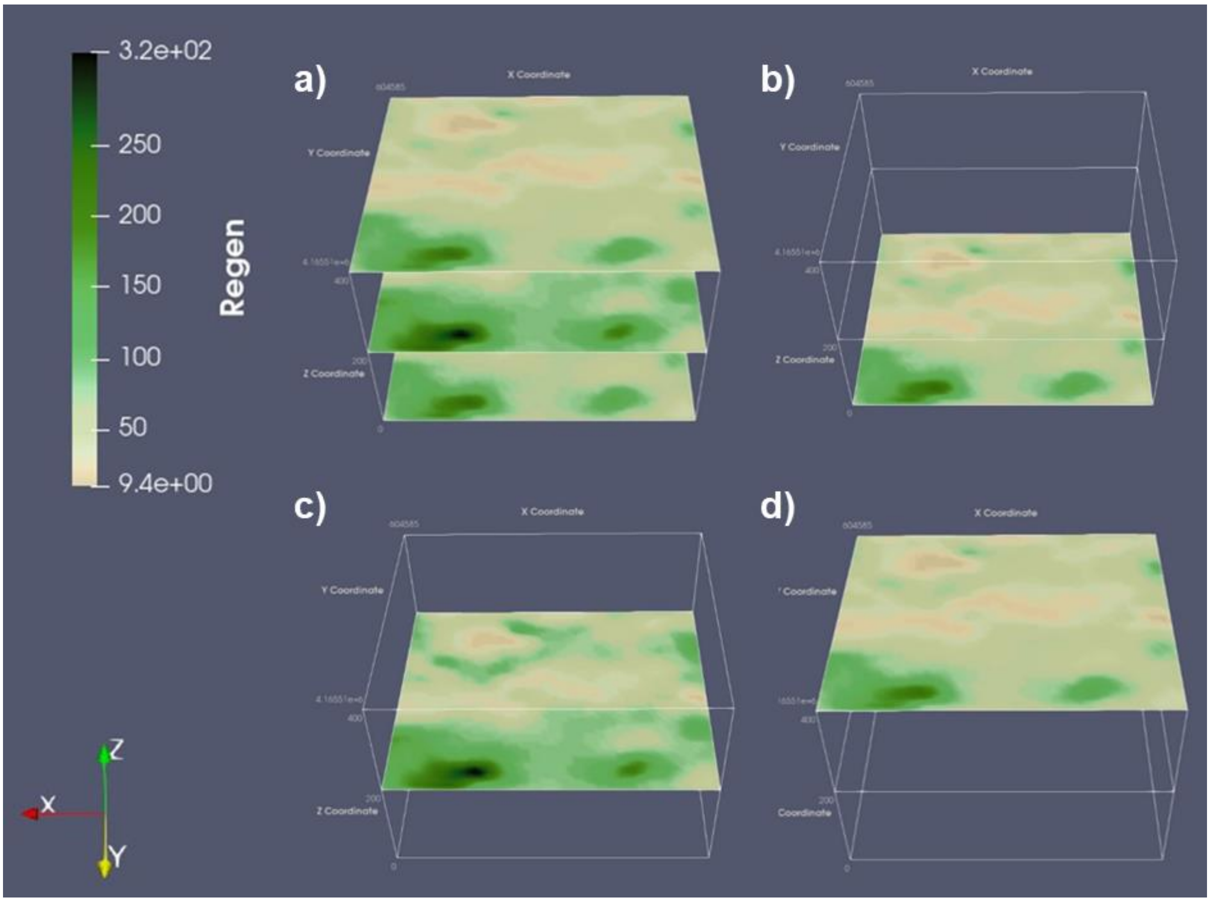

Figure 9 – Coloured cutting planes to analyse the evolution of regeneration rate (“Regen”) with time and climate change. Representation of a) all the cutting planes, b) the bottom plane, corresponding to the regeneration rate over a period of 30 years without climate change, c) the middle plane, corresponding to the regeneration rate over a period of 60 years without climate change, and d) the top plane, corresponding to the regeneration rate over a period of 60 years with climate change.

Generation of an animation over time

To better understand the evolution of the regeneration rate variable as a function of time and climate change, an animation using the Paraview software was generated. With the “Animation View” selected under the “View” menu, several keyframes were created using the editing parameters shown in Figure 10. To perform an animation that started at the bottom plane (30 years without climate change) and rose until the top plane (60 years with climate change), while passing through and briefly staying at the middle plane (60 years without climate change), “Sequence” animation using a “Slice Offset values” was used for the bottom plane. Additionally, the initial position of each plane was subtitled with text (“Sources” > “Alphabetical” > “Text”) using “Visibility” animation. This resulted in a 15-second animation with 900 frames (60 frames per second) that shows the evolution of the regeneration rates over a period of 30 to 60 years without climate change and over a period of 60 years in the absence and presence of climate change:

- Initially, a static shot of the plane corresponding to the regeneration rate data over a period of 30 years in the absence of climate change and its respective subtitle is shown during the first 3 seconds (Figure 11a).
- In the next 3 seconds, this plane moves along the z-axis from its initial position of 0 to 200, where it assumes the values corresponding to the regeneration rate data over a period of 60 years in the presence of climate change. By using a ramp interpolation, the regeneration rate values in-between these two positions are linearly interpolated (Figure 11b).
- The plane remains static during the next 3 seconds (Figure 11c).
- In the following 3 seconds, this plane moves along the z-axis from its previous position of 200 to 399, where it assumes the values corresponding to the regeneration rate data over a period of 60 years in the absence of climate change. By using a ramp interpolation, the regeneration rate values in-between these two positions are linearly interpolated (Figure 11d).
- Finally, a static shot of the plane is shown during the next 3 seconds (Figure 11e).

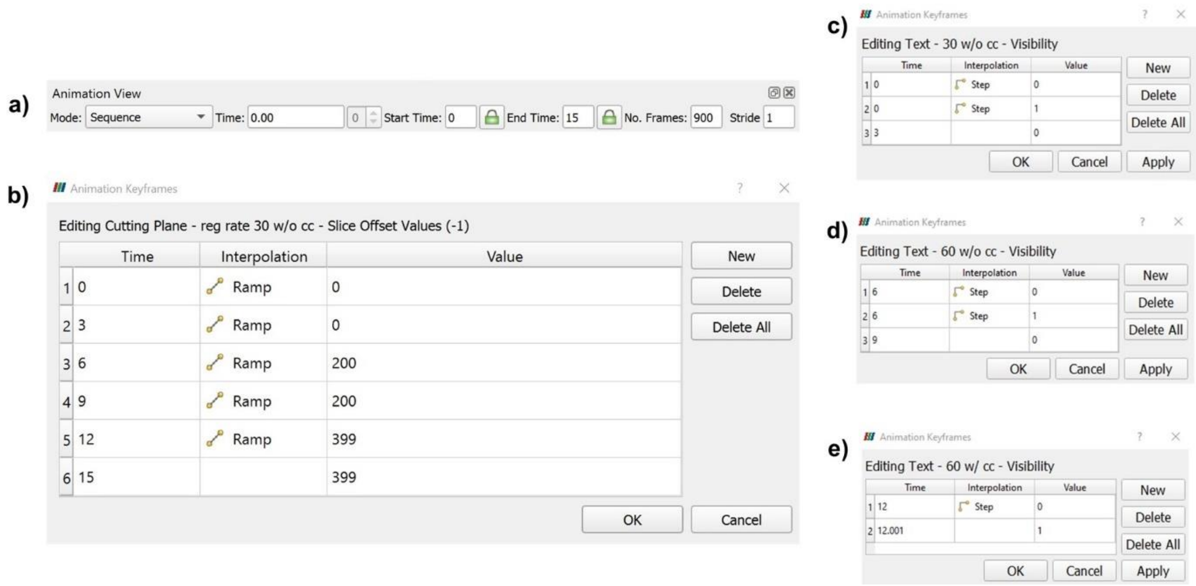

Figure 10 – Keyframe parameters used to create an animation to represent the evolution of the regeneration rate variable as a function of time and climate change. In a) the animation mode, duration and number of frames, b) slice offset animation used for the bottom plane, c) visibility animation used for the text of the bottom plane, d) visibility animation used for the text of the middle plane, and e) visibility animation used for the text of the top plane.

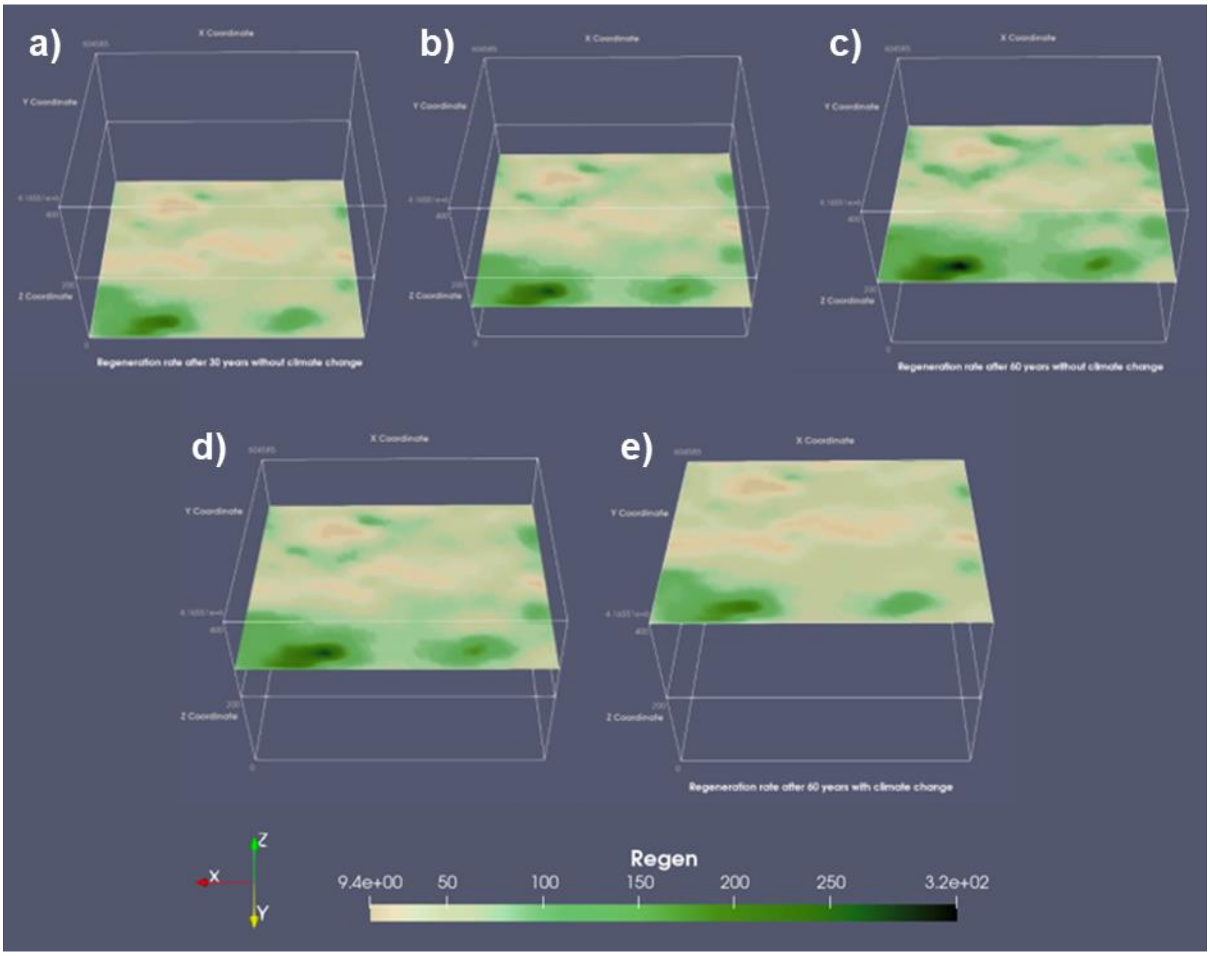

Figure 11 – Various animation frames during the animation generated in Paraview. In a) initial frame corresponding to the bottom plane, b) frame corresponding to the transition between the bottom and middle planes, c) frame corresponding to the middle plane, d) frame corresponding to the transition between the middle and top planes, e) frame corresponding to the top plane.

<u>Identification of the values corresponding to the centre of the interval of the regeneration rate in each plane</u>

To obtain the values corresponding to the centre of the interval of values of the regeneration rate in each plane, the “Contour” filter was applied sequentially for each of the three slices. After selecting “Contour by Regen”, the “Generate Number Series” was used to automatically generate the interval of regeneration rate values for each slice (Figure 12). By setting the interpolation type to linear and the number of samples to 3, the centre of the interval of values of the regeneration rate for each plane was obtained, as shown in Table 1. Each of the values corresponding to the centre of the interval of regeneration rate in the three planes were subsequently used to create the three isolines for each plane. To accomplish this, the “Contour” filter was again selected and the three centre values of the regeneration rate (118.510, 125.500 and 164.405) were introduced (Figure 12d).

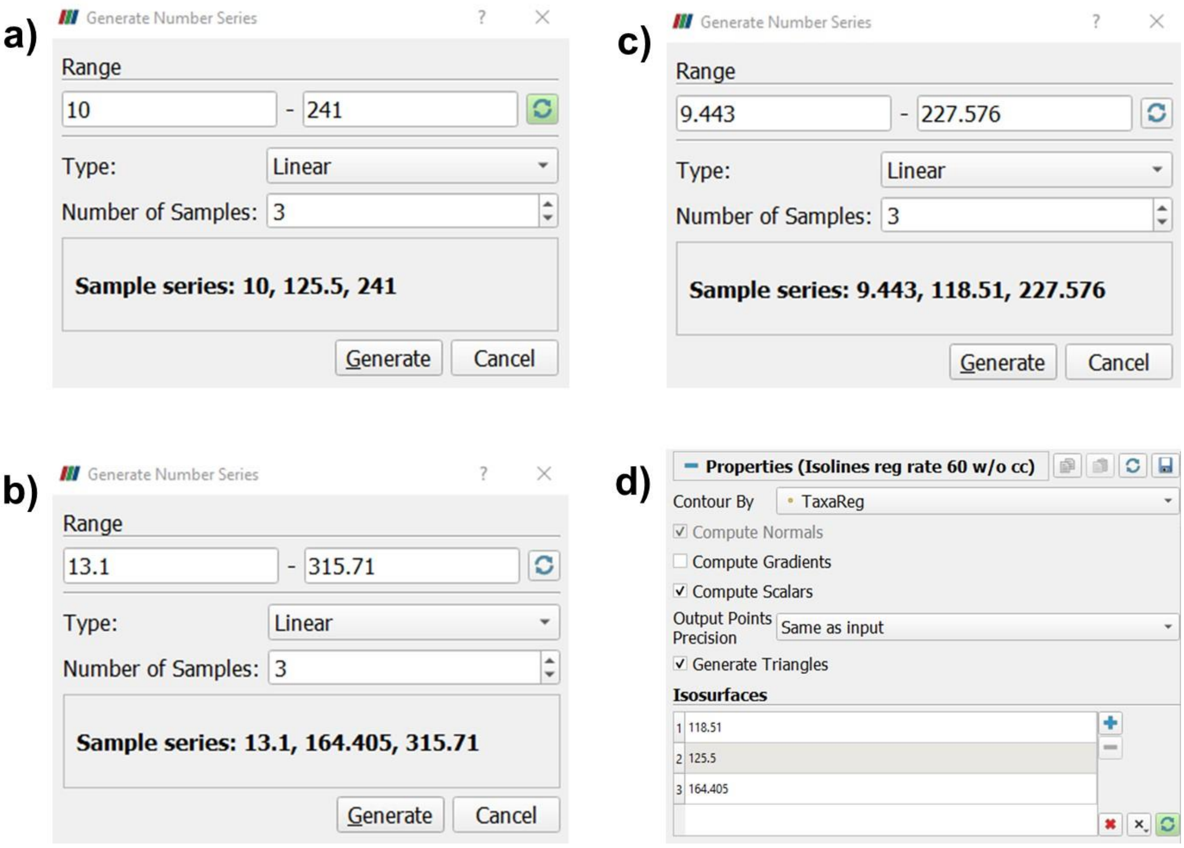

Figure 12 – Identification of the centre of the interval of values of the regeneration rate. In a) centre of interval for the bottom plane, b) centre of interval for the middle plane, c) centre of interval for the top plane, and d) introduction of the three centre values in the middle plane to create the isolines.

Table 1 – Interval and centre values obtained for each plane using the “Value Range” option of Paraview. The centre of the interval of values of the regeneration rate is indicated in bold.

Range values	Bottom Plane (regeneration rate over 30 years without climate change)	Middle Plane (regeneration rate over 60 years without climate change)	Upper Plane (regeneration rate over 60 years with climate change)
Bottom	10.000	13.100	9.443
Centre	**125.500**	**164.405**	**118.510**
Top	241.001	315.710	227.576

The results obtained from the centre of the interval of values of the regeneration rate for each plane can provide initial insight on the average values that will be shown on each plane for the regeneration rates. It is possible to see that both the bottom and upper planes have similar centre values while the middle plane has a higher value when compared with the other two. This phenomenon is also seen for the minimum and maximum range values, which could indicate that both the regeneration rate over 30 years without climate change and the 60 years with climate change are similar.

The cutting planes with the corresponding isolines are shown in Figure 13. The colour palette chosen to represent the three isolines was custom made by selecting the “Edit” and “Interpret Values As Categories” option (Figure 14). A blue colour palette was chosen to represent the isolines because it gave the most perceivable contrast with the green coloration of the surfaces. For consistency, darker blues were attributed to higher values of regeneration rate, similarly to dark green colour chosen to represent areas with greater values of the same variable.

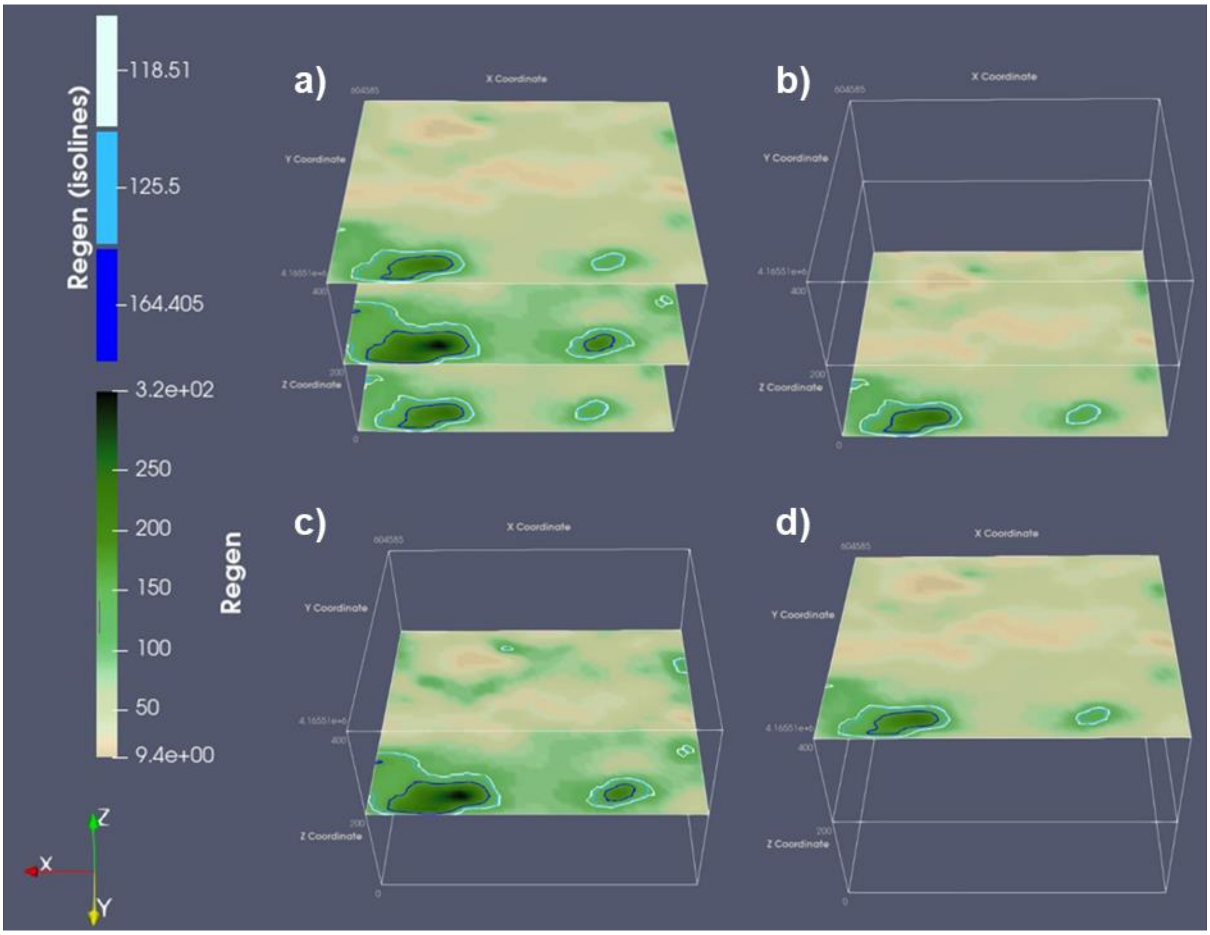

Figure 13 – Coloured cutting planes and respective isolines. a) Isolines superimposed over each of the coloured cutting planes. (b) Isolines superimposed over the bottom plane (30 years without climate change). (c) Isolines superimposed over the bottom plane (60 years without climate change). (d) Isolines superimposed over the top plane (60 years with climate change).

As observed from Figure 13, the area within the isolines is greater in the middle plane corresponding to the regeneration rate over a period of 60 years without climate change. Furthermore, it can also be seen that the isolines are similar in distribution and size between the bottom and top planes corresponding to the regeneration rate over a period of 30 years without climate change and 60 years with climate change, respectively. Therefore, from the isoline representation, it is possible to conclude that the regeneration rate increases as a function of time and in the absence of climate change.

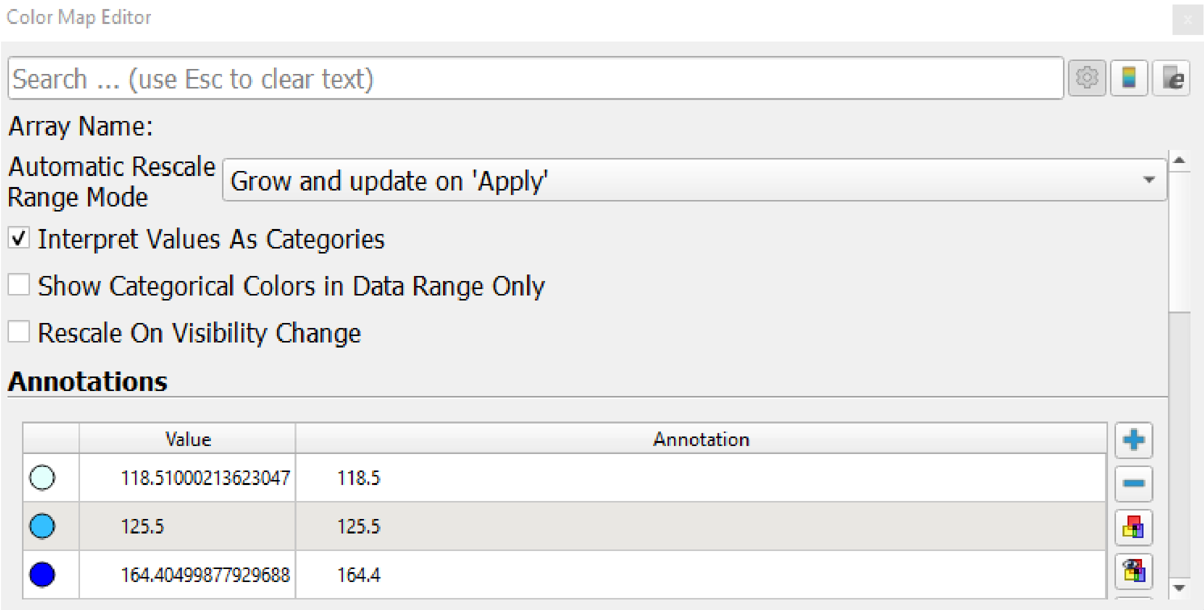

Figure 14 – Parameters chosen to create the colour palette associated with the “Regen” isolines.

<u>Creation of isosurfaces corresponding to the values chosen for the “Regen” isolines</u>

The next phase of the project was to generate isosurfaces connecting the same “Regen” values across the 3D space. To accomplish this, the “Contour” filter was applied directly to the full data set using the values corresponding to the centre of the interval of regeneration rate for each individual plane (118.510, 125.500 and 164.405), as shown in Figure 15. An opacity value of 0.17 was applied to make the visualisation clearer. The resulting isosurfaces are illustrated in Figure 16.

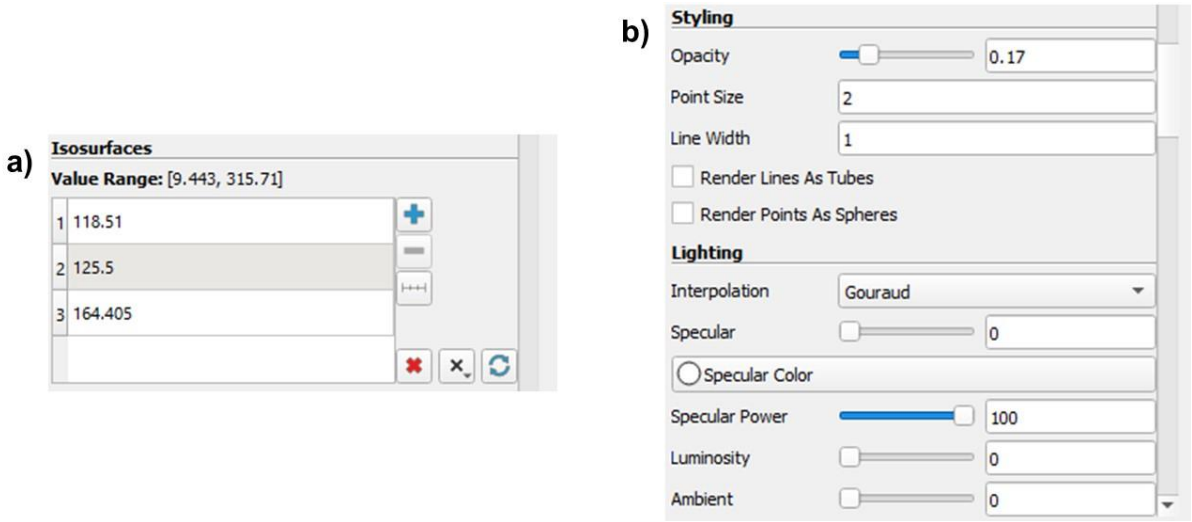

Figure 15 – Parameters used to create the isosurfaces. In a) "Regen" scalar values, and b) respective styling options.

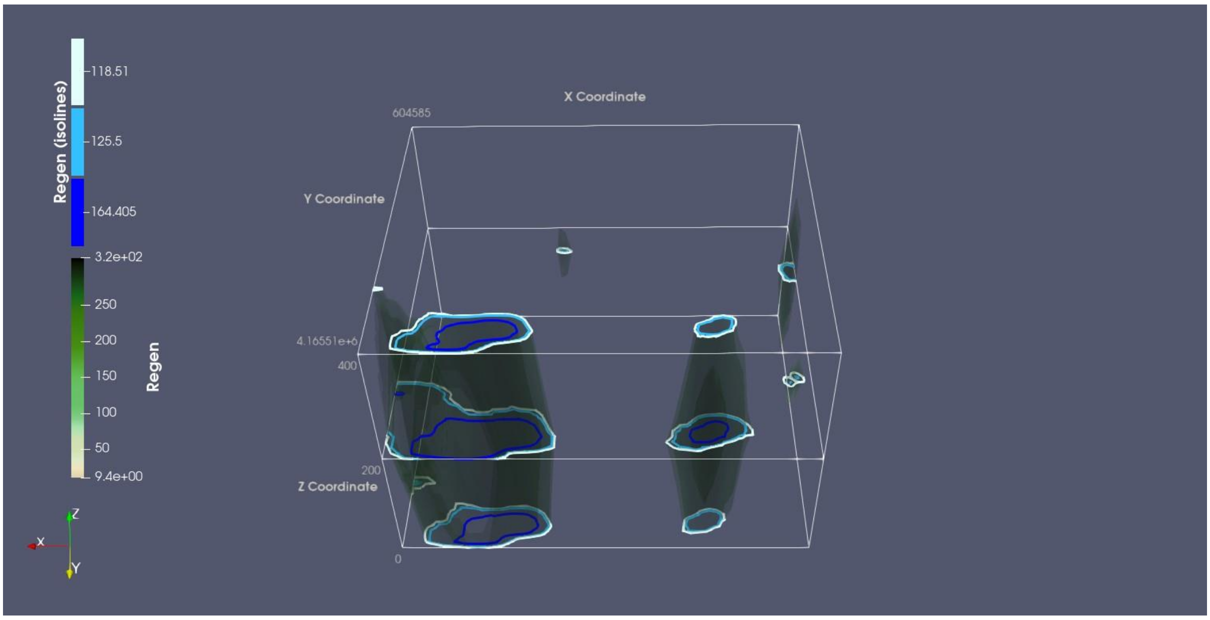

Figure 16 – Visual representation of the isosurfaces corresponding to the centre of the interval of regeneration rate values and respective isolines.

As seen in Figure 16, it is possible to visualise an increase of the isosurface volume, starting from the bottom plane (30 years without climate change) until reaching the second plane (60 years without climate change). New zones also emerge in the latter, indicative of higher regeneration rate values in this plane. On the other hand, when comparing the middle plane with the top plane (60 years with climate change) a decline in the volume and number of the isosurfaces can be seen. This is indicative of the decrease in the regeneration rate values that occurs in the presence of climate changes.

Using a representation that includes both isolines and isosurfaces, it is possible to obtain a better understanding of the evolution of the regeneration rates as a function of time and climate change.

Representation of the terrain orography in each plane.

The next step in the analysis was to evaluate the potential impact of orography on the regeneration rate of the holm oak trees. Initially, cutting planes were coloured according to the scalar variable “Altitude” to obtain a basic understanding of the orography (Figure 17). The applied colour pallet has darker colours (purple) associated with lower altitude values and brighter colours (yellow) in areas with greater altitude values. This colour palette was one of the predefined in Paraview (Inferno) and was chosen since it is one of the most applied to represent altitudes, making it intuitive. As expected, differences in colour across planes are not observable, because the same scalar “Altitude” values were given for each.

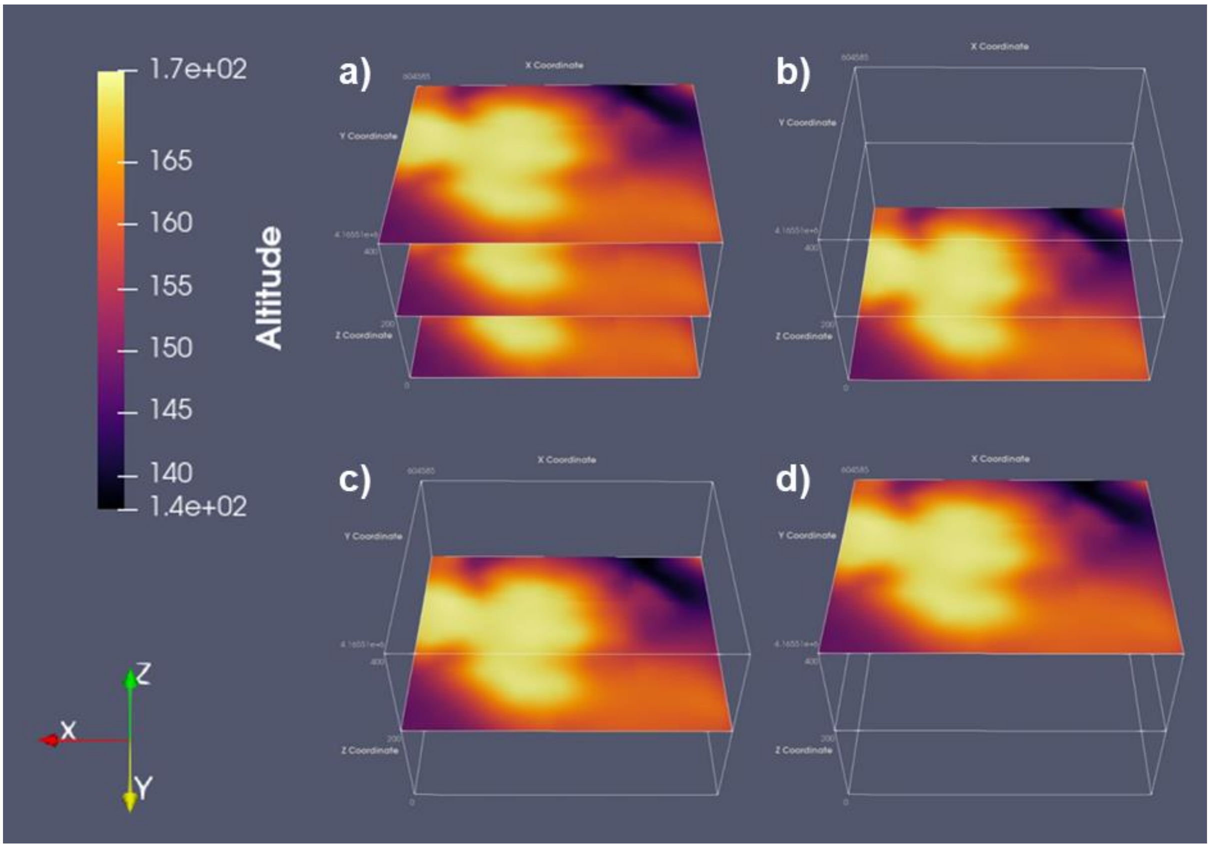

Figure 17 - Visual representation of “Altitude” for each plane with the chosen colour palette (Inferno). (a) Representation of “Altitude” for all the planes. (b) Representation of “Altitude” for the bottom plane. (c) Representation of “Altitude” for the middle plane. (d) Representation of “Altitude” for the top plane.

To obtain a more visually intuitive representation of the orography in a three-dimensional environment, each plane was warped according to the scalar “Altitude” values. To do this, a “Carpet Plot” algorithm was applied by using the “Warp by Scalar” filter with a scale factor of 2.5 in Paraview. The properties attributed to this filter can be observed in Figure 18.

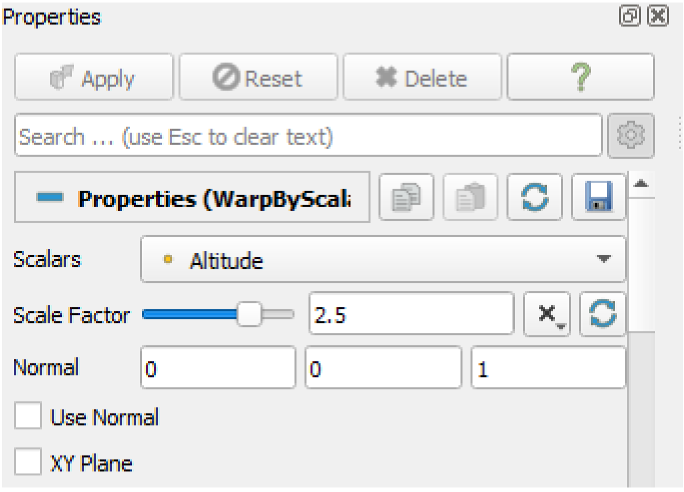

Figure 18 – Properties chosen in the “Warp by Scalar” filter to represent the terrain orography in each plane.

However, using the “Warp by Scalar” filter translated all the planes to higher coordinates of z. To overcome this, the "Transform" filter was used (with a z of -370) to move the planes to their initial position, as seen in Figure 19.

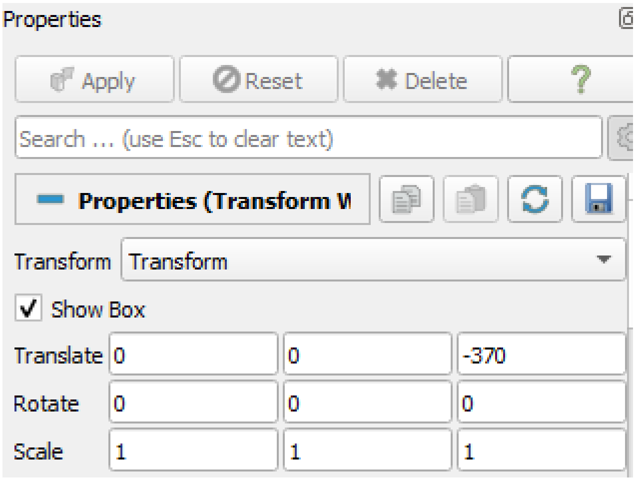

Figure 19 – Properties chosen in the “Transform” filter to translate each plane to their original Z position.

Following all these steps, it was then possible to reproduce the orography of the terrain in a three-dimensional environment, as seen in Figure 20. To reinforce the warp representation, the same colour palette (Inferno) was applied to the orography.

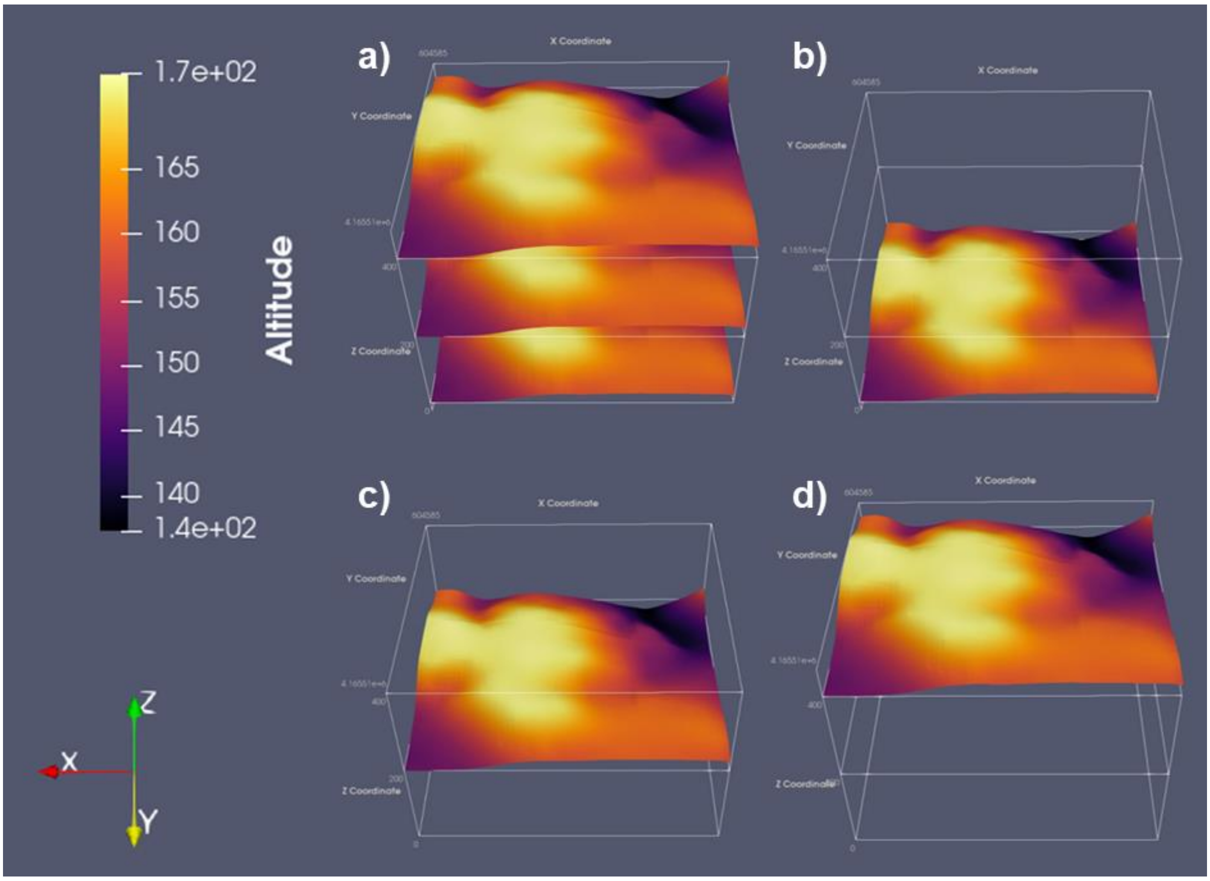

Figure 20 – Visual representation of the "Altitude" variable for each plane, both by warping and colouring the surface. In a) Representation of the warped and coloured surface according to the "Altitude" scalar variable for all planes, b) for the bottom plane, c) for the middle plane, and d) for the top plane.

To evaluate the if the altitude of the terrain could affect the regeneration rate in the study area, the warped representation was coloured according to the colour palette previously used for the "Regen" variable. These representations can be seen in Figure 21.

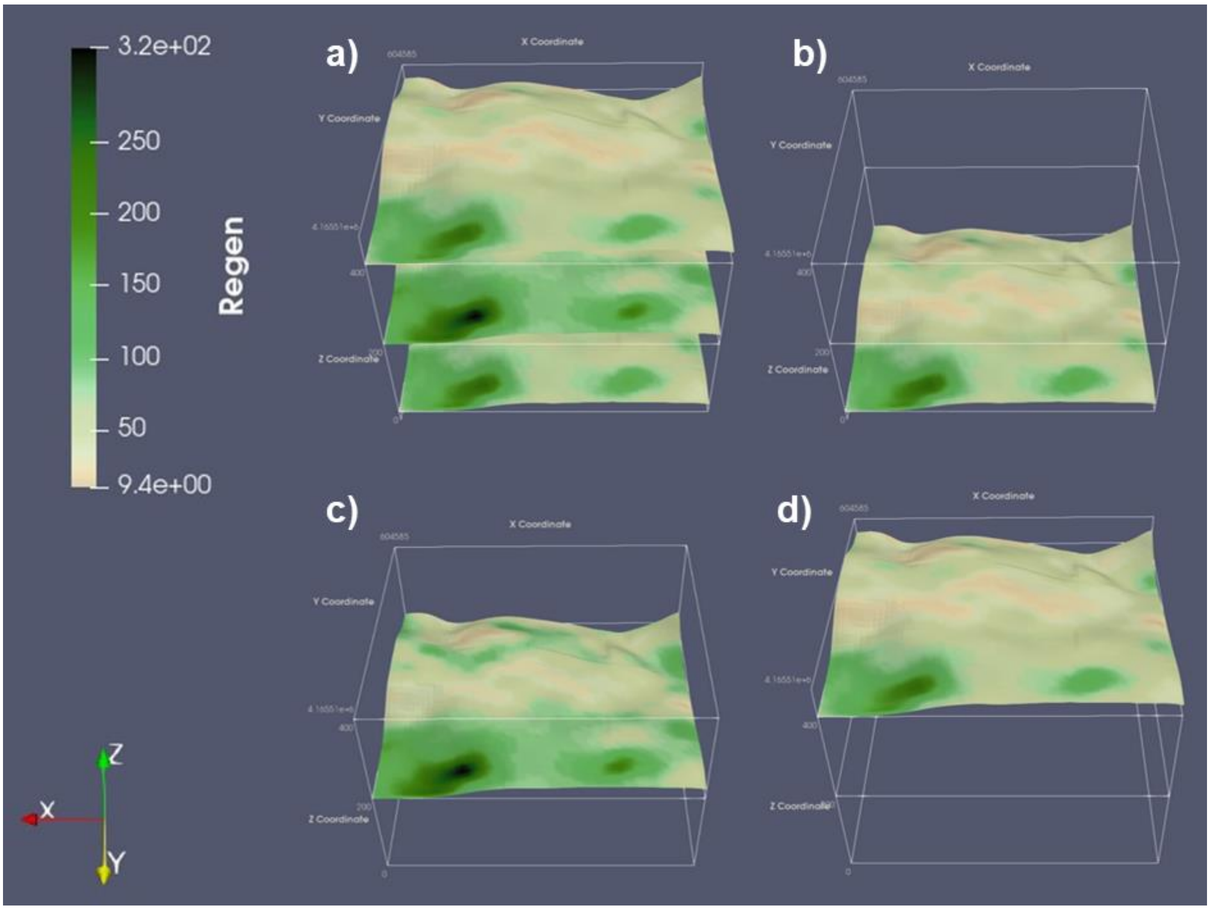

Figure 21 – Visual representation of the terrain for each plane, with warping by “Altitude” and colouring by “Regen”. a) Representation of the warped surface according to the “Altitude” scalar variable, coloured according to “Regen” for all planes, b) for the bottom plane, c) for the middle plane, d) for the top plane.

Several conclusions can be made from Figure 21. Similarly, to what had been observed previously for planes coloured according to the “Regen” variable (Figure 9), the regeneration rate increased as a function of time and decreased with climate change.

When the terrain orography is considered, it is possible to observe that areas with higher regeneration rates are located in a valley in the northeast region of the study area. With this information, a hypothesis can be made in which lower altitudes are associated with higher regeneration rates. However, the altitude of the study area does not change significantly (from 140 to 170 m). As such, it is unlikely that the regeneration rate would be affected by altitude to a significant extent. Additionally, there are areas with low altitudes that do not show high regeneration rates, particularly in the southwest.

Representation of the orography of the terrain with isolines more appropriate to analyse the regeneration rate data

The representation of orography with isolines was tackled in two distinct ways: (1) by colouring the warped surface by “Altitude” and applying isolines based on “Regen”, and (2) by colouring the warped surface by “Regen” and applying isolines based on “Altitude”. Both possibilities were tested to evaluate which one gave a more understandable representation.

For possibility 1, named group A, the isoline values were manually changed to provide a better representation of the differences in regeneration rate between the three planes. The new isoline values were: 100, 150, 230. For representation 2, named group B, the values of the isolines were chosen based on a linear interpolation for the range of values of “Altitude”. A total of 10 isolines were chosen in order to visualise a vast range of altitudes: 137.22; 141.12; 145.01; 148.91; 152.81; 156.70; 160.60; 164.50; 168.40; 171.30.

These distinct possibilities were applied to each z plane and can be seen in Figure 22.

When comparing the A group representations, which use colouring based on “Altitude” and isolines based on “Regen”, it is possible to visualise an increase of the regeneration rate from the lower plane (30 years without climate change) to the middle plane (60 years without climate change) indicated by the growth of the area by each isoline and the emergence of new zones entirely. From the middle plane (60 years without climate change) to the top plane (60 years with climate change) the reverse effect can be seen. In this case, the regeneration rate diminishes, corroborated by the reduction in the area encompassed by each isoline and the disappearance of some zones.

A comparison between the bottom plane (30 years without climate change) and the top plane (60 years with climate change) now reveals clear differences between the two. In the northeast region, it is possible to visualise the disappearance of the isoline that represents the “Regen” scalar value of 230 in the top plane, as well as a reduction in area encompassed by the isoline with a “Regen” value of 100. In the northwest region, the isoline associated with the “Regen” value of 150 disappears in the top plane. As such, it is possible to conclude that the existence of climate change severely impacts the regeneration rate of the terrain, which could lead to a setback of more than 30 years. In practice, these conclusions make sense, since climate change tends to lead to more extreme temperatures, droughts and deforestation which could result in more arid terrains, making holm oak regeneration more difficult [2].

These representations also allow a discussion of the correlation between altitude, which could also be tied with sun exposure, and the regeneration rate of the holm oaks. From the representations, it is possible to assess that for any of the three planes, the two isolines with the greatest “Regen” values are not present in areas with the highest “Altitude” values. Additionally, higher regeneration rates are further away from the highest altitude point. As such, it is possible to conclude that higher altitudes lead to smaller regeneration rates.

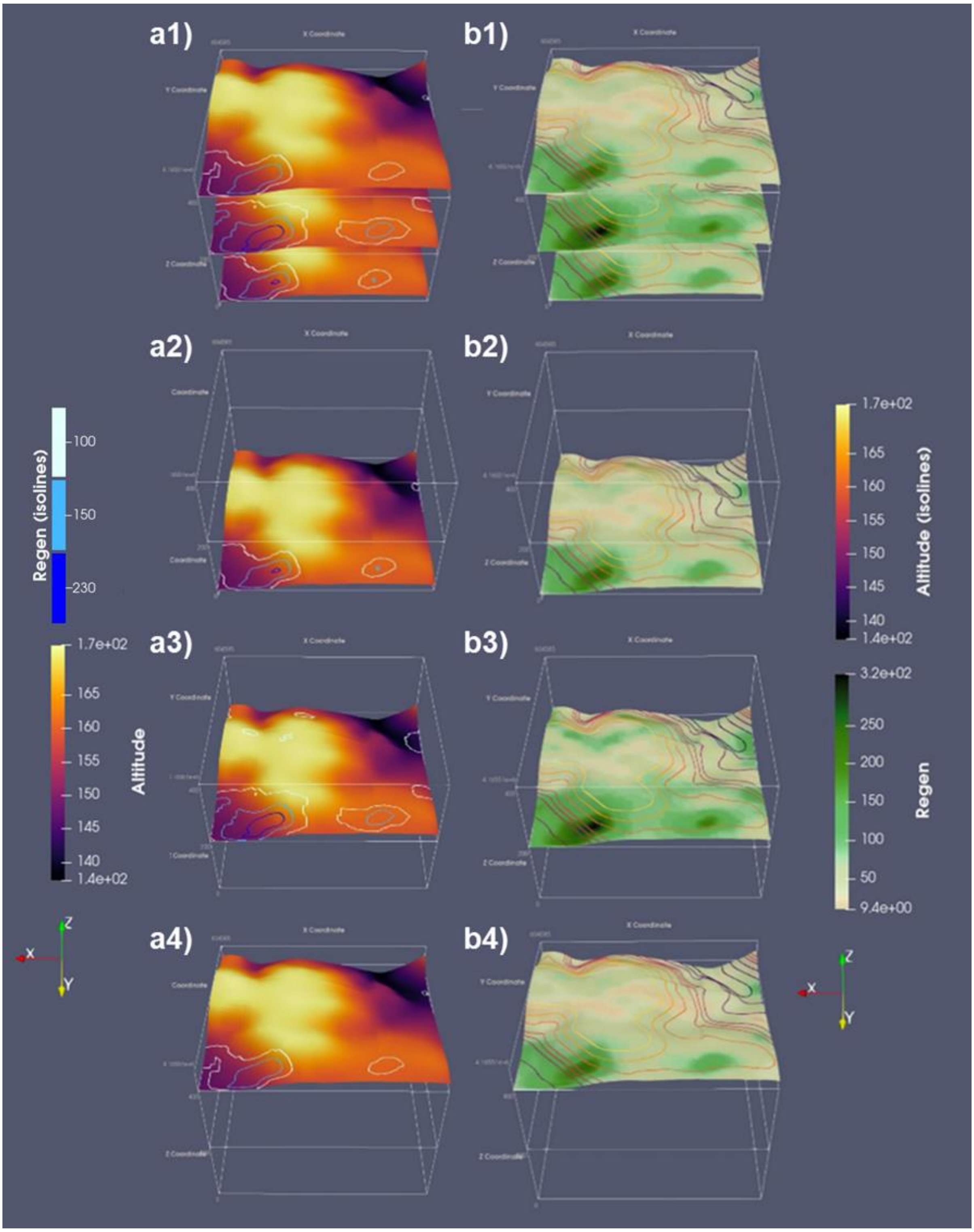

Figure 22 – In group a) visual representation of the terrain for each plane, with warping by “Altitude”, colouring by “Altitude” and isolines using “Regen” values. In group b) visual representation of the terrain for each plane, with warping by “Altitude”, colouring by “Regen” and isolines using “Altitude” values. For a1, b1) all planes, a2, b2) bottom plane, a3, b3) middle plane, a4, b4) top plane.

When trying to understand if sun exposure has any correlation with the regeneration rate of holm oaks, two distinct possibilities can be thought of. For the first possibility, climate change could lead to more deforestation, which, in turn, would lead to more arid terrains and increased sun exposure. In this case, it could be concluded that higher sun exposure would result in a decrease of the regeneration rate of holm oaks. For the second possibility, the sun exposure could decrease adjacently to higher altitude zones due to shading provided by the terrain orography. For this scenario, lower altitude zones could be shaded by adjacently located higher altitude zones, leading to less sun exposure. In this case, it could be concluded that lower altitudes are less exposed to the sun, which would result in an increase of the regeneration rate of holm oaks.

To correlate regeneration rate with sun exposure, the terrain was identified on a map by introducing its coordinates in ArcGIS Pro and converting the resulting polygon to Google Earth. The resulting terrain visualisation is shown in Figure 23.

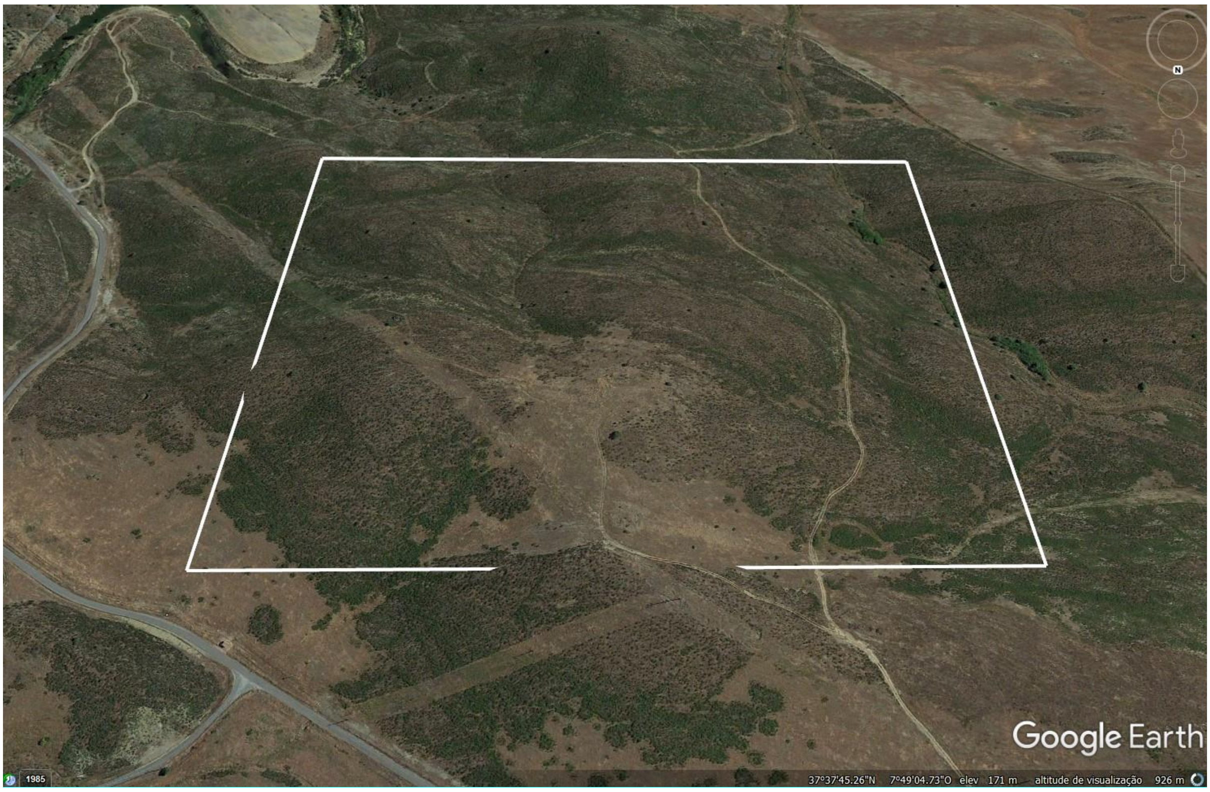

Figure 23 – Real representation of the terrain and corresponding orography by using Google Earth.

Considering the A group representations in Figure 22, this phenomenon can be contextualised by the location of the isolines. As seen for any of the planes, the isolines that correspond to higher values of “Regen” are located in the north region, with two distinct zones in northeast and northwest. It is reasonable that higher “Regen” values are located in the north area of the terrain because they receive less sun exposure than those located in the south area [3], and these do not have an adjacently located area with higher altitude, capable of casting shade onto these southern regions. The difference in regeneration rate between northeast and northwest can be conceptualised by variations in the shading provided by the adjacently located areas. Considering that the sun rises in the east and sets in the west, the northeast region receives shade throughout the day, while the northwest region is only shaded in the morning. This phenomenon is exemplified in Figure 24.

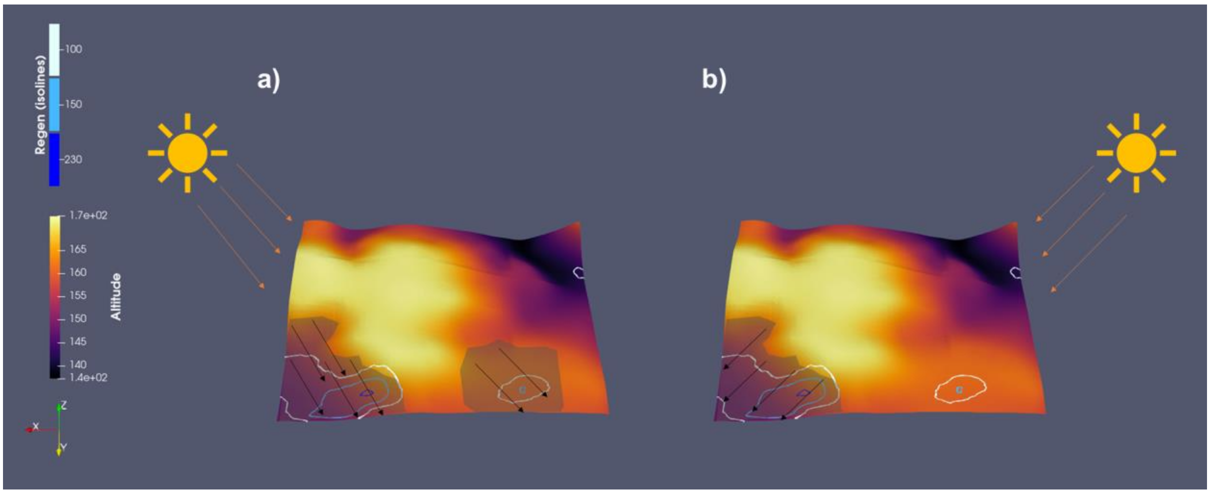

Figure 24 – Illustration of the differential effect of sun exposure according to variations in the terrain orography. In a) when the sun rises in the east, the north regions are shaded by adjacently located areas with higher altitude, while the south regions remain unprotected from solar radiation. In b) when the sun sets in the west, only the northeast region remains shaded by adjacently located areas with higher altitude, while the northwest region is now unprotected from solar radiation.

Regarding the B group representations in Figure 22, one could claim that the isolines are not an insightful addition. A simpler and arguably more understandable visualisation could be made without them because the same information regarding the terrain orography is already implied in the warping of the representation. Nevertheless, the conclusions made previously for group A could be applied here as well. The difference is that they would be obtained by an increase in the green coloration on the surface of the representation, instead of the area encompassed by each isoline.

The choice of which group of representations is more understandable is obvious. Group A uses the default colouring scheme for altitude and makes use of isolines for visualising differences in the regeneration rate of the terrain across distinct z planes, which is easily understandable and comparable. Group B uses a colouring scheme that makes sense for the regeneration rate, making it easy to understand. However, the isolines do not provide additional insight on what the warp is already showing and could actually induce confusion. Furthermore, since differences in the regeneration rate are only seen by colouration, it is harder to compare different planes and to discern different colours. As such, group A representations were deemed more favourable.

Creation of glyphs to display the vector quantity “RegenerationTrend”

To represent glyphs of the “RegenerationTrend” in each plane, some notions should be considered. First, considering the vector quantities created in the VTK file, it does not make sense to represent “RegenerationTrend” in the middle plane (60 years without climate change), since the vector quantities are null. Second, the correct glyphs for vectors should be considered and these are typically arrows.

To make arrow glyphs, the "Glyph" filter was applied to the first and third planes, as shown in Figure 25a. The glyph type was set to arrow, the orientation array was based on the vector variable (“RegenerationTrend”), the scale array was set to none, the maximum number of sample points was lowered from 3000 to 250 (to allow a better understanding of the representation) and the colouring of the glyphs was done based on the magnitude of the vector variable using the previously defined Regen colour palette.

To further enhance the understandability of these representations, 45º lines were added to each plane, as shown in Figure 25b. This was performed by applying the “Steam Tracer” filter to the original plane, setting the first point of the line to the origin of the data and the second point to the value of the fiftieth point of the X and Y coordinate.

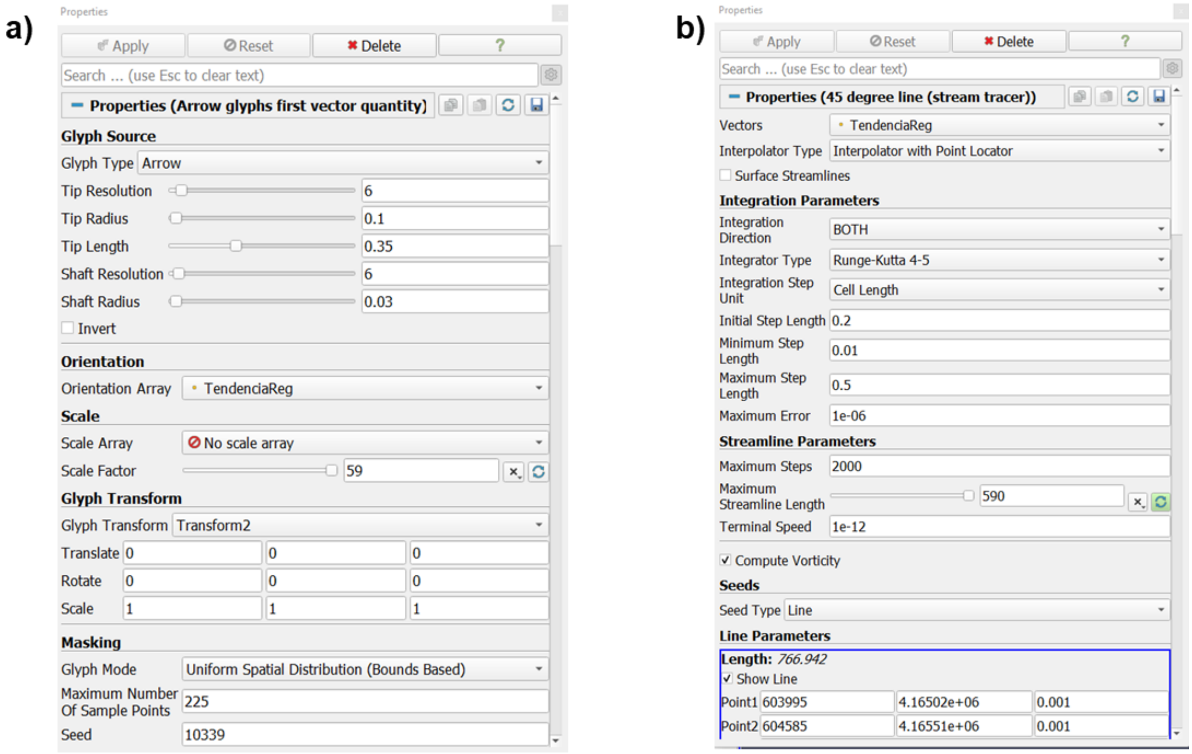

Figure 25 – Parameters used for glyph representations. In a) the properties of the glyphs, and b) the properties of the 45º line.

The representations obtained for the bottom and top planes can be seen in Figure 26.

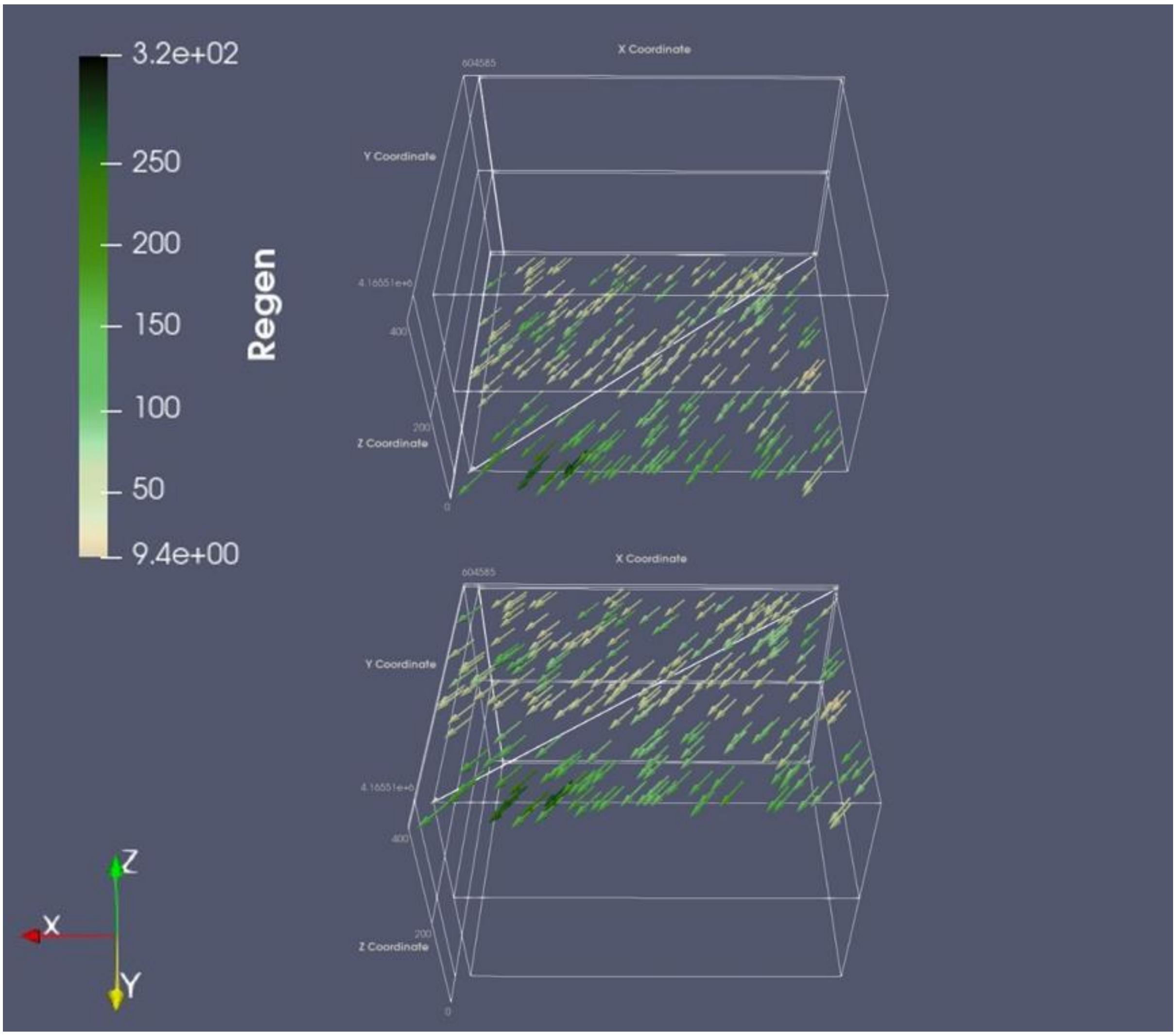

Figure 26 – Visual representation of the vector variable “RegenerationTrend” associated with a) bottom plane, and b) top plane.

There are two important features to consider in these representations: the colour and the orientation of the vectors. The colour provides an indication of the vector magnitude, which considers the individual values of each of the dimensions of the vector (3 dimensions in this case). Since the first two dimensions of the vectors are composed by the scalar values of the regeneration rate and the third dimension is null, the colour of the vectors is indicative of the regeneration rate. Darker vectors indicate a higher regeneration rate, while lighter vectors indicate the opposite. This information was already obtained in other representations, but it is still a good addition. The orientation, on the other hand, can provide new relevant information about which of the two dimensions of the vector has higher values of regeneration rate.

In the case of the bottom plane, the vector quantity is described as follows: the first dimension corresponds to the scalar quantity of the regeneration rate after 30 years without climate change, while the second dimension corresponds to the scalar quantity of the regeneration rate after 60 years without climate change. By using a 45º line, it is possible to visualize that the orientation of these vectors tends slightly to the second dimension, since they have an inclination higher than 45º. Therefore, it is possible to conclude that the regeneration rate is higher after 60 years without climate change.

In the case of the top plane, the first dimension corresponds to the scalar quantity of the regeneration rate after 60 years with climate change, while the second dimension corresponds to the scalar quantity of the regeneration rate after 60 years without climate change. In this case, the orientation of the vectors tends slightly to the second dimension. Thus, it is possible to conclude that the regeneration rate is higher after 60 years without climate change.

These conclusions corroborate the previously obtained results using the scalar variable “Regen”, with both types of representations showing higher regeneration rates over a period of 60 years in the absence of climate change.

Representation of “Regen” as spherical glyphs on warped by “Altitude” surfaces

Another way to visualise and interpret the data would be to consider the elevation of the terrain and try to represent the regeneration rates of the holm oak trees using glyphs. To achieve this, coloured warps were combined with spherical glyphs to represent the regeneration rates in each point. To obtain glyphs, the “Glyph” filter was applied on the already warped surface and the settings were changed to represent “Regen” as a function of size and colour of the spheres. The settings used to create the glyphs can be seen in Figure 27. This methodology was applied to all planes and the results can be observed in Figure 28.

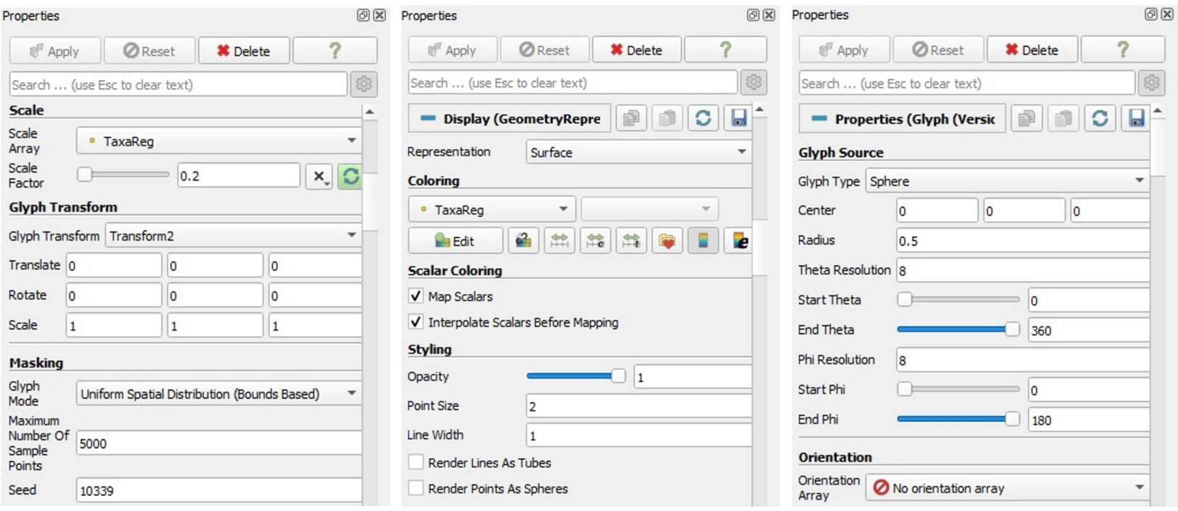

Figure 27 – Various property settings used for the creation of the spherical glyphs to represent “Regen”.

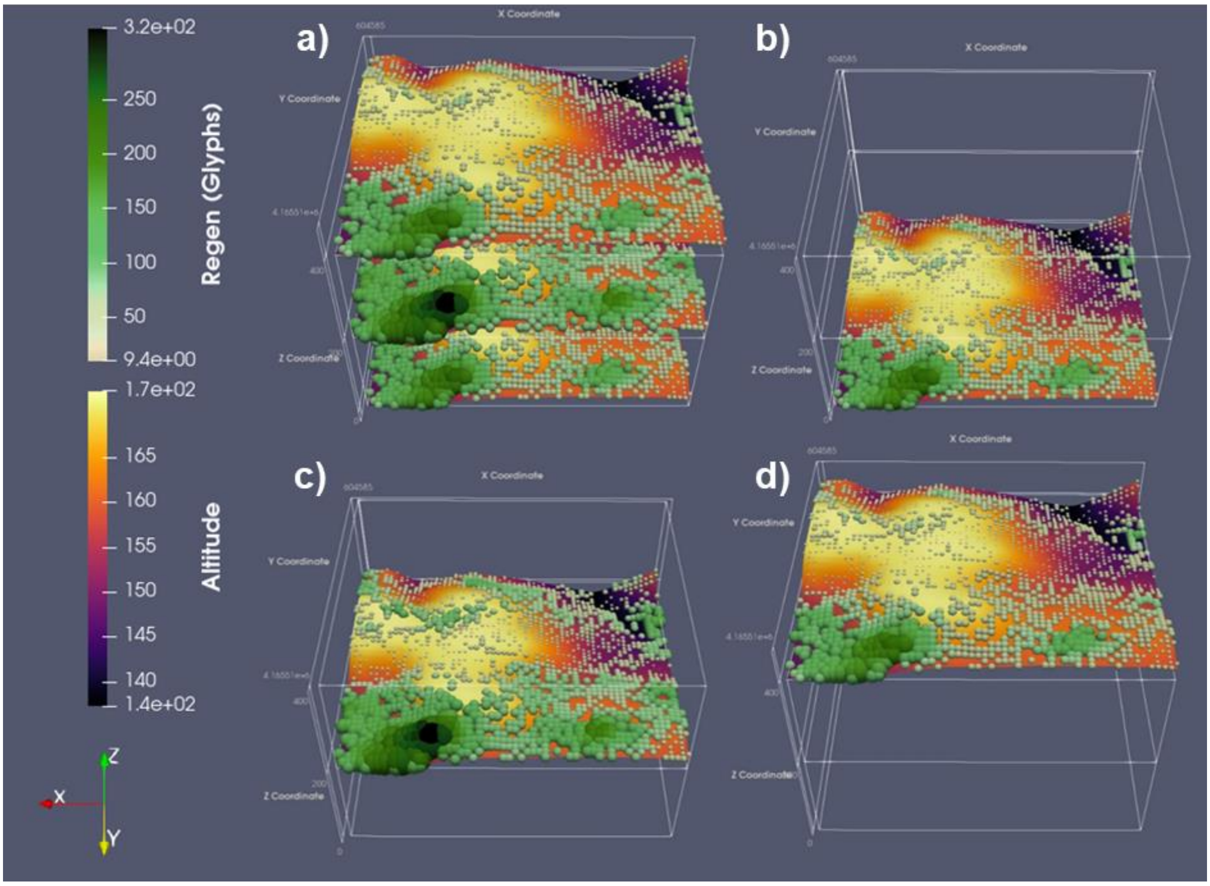

Figure 28 – Visual representation of the terrain for each plane, through warping and colouring by “Altitude” and with spherical glyphs representing “Regen”. In a) all planes, b) bottom plane, c) middle plane, and d) top plane.

As seen in Figure 28, the areas with greater regeneration rate display spherical glyphs with darker green colours and greater size. The overlap of warped surfaces with the spherical glyphs provides a more detailed representation that allows an easier distinction between “Altitude” and “Regen” across the three planes. Furthermore, certain zones that did not have any information using previous representations, such as those using warp with “Regen” isolines, now exhibit more information regarding the regeneration rate of the terrain. Thus, the addition of this representation corroborates previously obtained results and facilitates the analysis of the regeneration rate of holm oaks between distinct planes and within each plane.

IV. Conclusions

The visualisation of the predicted data using the Paraview software allowed the evaluation of the effect of time, climate change and sun exposure on the regeneration rate of holm oak trees in agriculturally abandoned lands in Alentejo.

It was possible to conclude that the regeneration rate increases with time because higher “Regen” values were observed from a time period of 30 to 60 years. On the contrary, the regeneration rate diminishes with climate change since lower “Regen” values were observed when considering climate change in a time period of 60 years. This result can be explained by the effect of climate change on deforestation which increases sun exposure in previously shaded terrains. Furthermore, the southern region had lower regeneration rates when compared to regions located in the north, particularly in the northeast, because the latter are more shaded due to the elevated orography of the adjacently located areas.

V. References

[1] A. Príncipe, A. Nunes, P. Pinho, L. do Rosário, O. Correia, and C. Branquinho, “Modeling the long-term natural regeneration potential of woodlands in semi-arid regions to guide restoration efforts.,” *Eur J For Res*, vol. 133, no. 4, pp. 757–767, 2014.

[2] A. G. Barnston, R. E. Livezey, and M. S. Halpert, “Modulation of Southern Oscillation-Northern Hemisphere mid-winter climate relationships by the QBO,” *J Clim*, vol. 4, no. 2, pp. 203–217, 1991, doi: 10.1175/1520-0442(1991)004.

[3] M. G. Kimlin, “Geographic location and vitamin D synthesis,” *Mol Aspects Med*, vol. 29, no. 6, pp. 453–461, Dec. 2008, doi: 10.1016/J.MAM.2008.08.005.