4.1.4 SET3: Trade-offs and joint optimality

This set of runs revealed the potential existence of trade-offs between different couples of management objectives and mapped the joint optimality on the spatial allocation of projects across each managing landscape. We note here that a couple of objectives do not necessarily mean the existence of trade-offs. These trade-offs were examined at the scale of FS districts. In addition, although some FS districts might show strong trade-offs, others might have none. The first couple examined the community exposure sources vs. the protected area sources. The map in Figure 35 shows a solution of approximately 32,500 ha for the three examined weight combinations (equal, 10-3 and 3-10) and creates a maximum difference of 0.4% in the attainment of both the community exposure sources and protected areas exposure sources. Blue- and orange-coloured projects that overlap with the equal weighing scheme are not visible, and they only appear where these projects were not selected by the other two weighting schemes. The overall attainment for the management objective of community exposure sources is approximately 6%, while for the protected areas approximately 10.5%. Most of the projects spatially coincide and only few differentiate at the FS districts of Patra and Sparti for the weight combination 10-3 (orange colour), and few in Tripoli and Sparti for the weight combination 3-10 (blue colour).

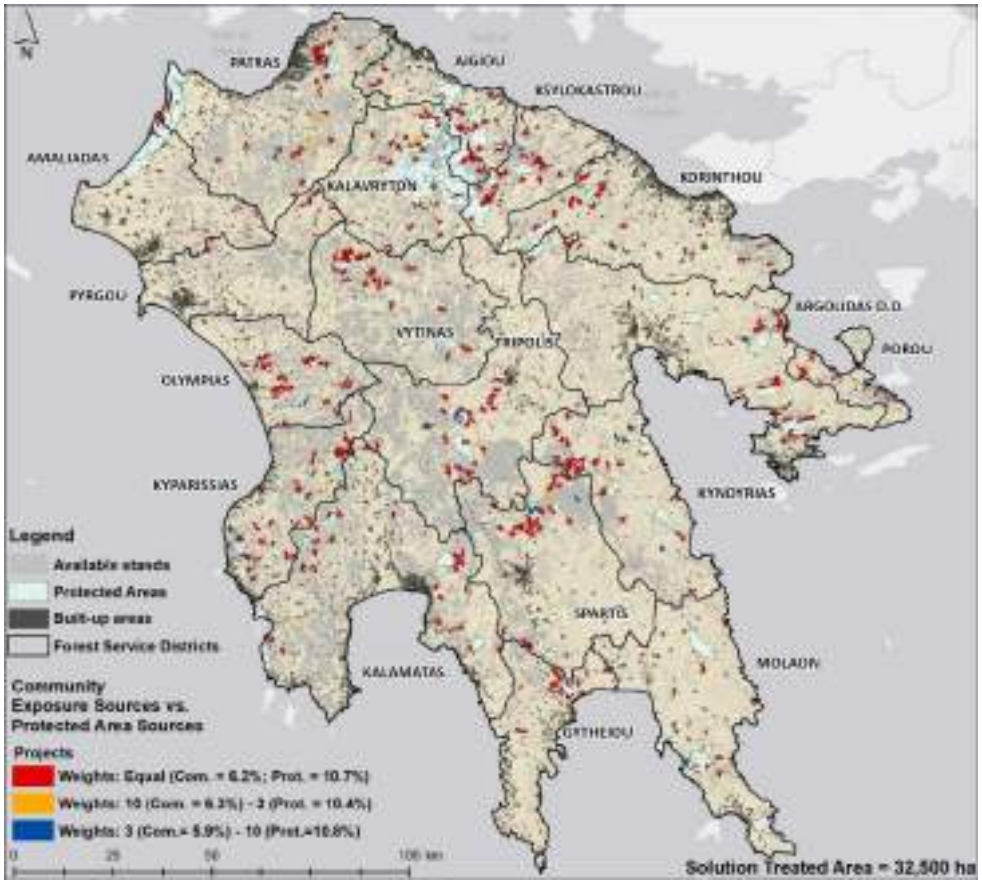

Figure 35 Trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Developed areas exposure sources objective weight maximized (10) and protected areas exposure sources set to low (3) (orange); c) Protected areas exposure sources objective weight maximized (10) and developed areas exposure sources set to low (3) (blue).

The trade-off graph in Figure 36 shows some shared differences in the FS districts of Korinthou (i.e., the more the attainment of the protected areas is increased, the more the community exposure is decreased), Molaon and Kalamatas. Most of the remaining FS districts either show minor and insignificant changes in the attainment, or had a joint optimality, i.e., the increase in attainment on one objective had an increase also in the other (e.g., Kalavryton or Kynourias) or were stable like the cases of Kyslokastro and Aigio where the attainment of community exposure remained approximately at the same levels while the attainment of the protected areas was increasing.

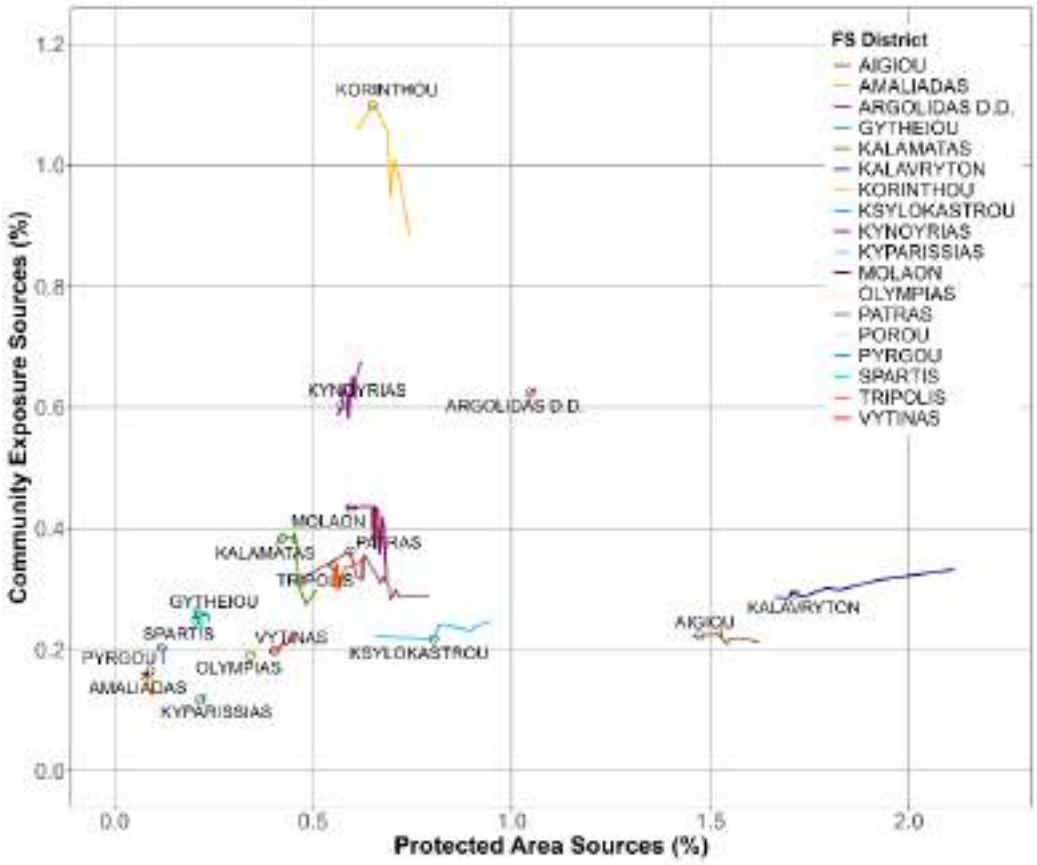

Figure 36 Trade-off production probability curves for each Forest Service District for the objectives of developed areas exposure sources vs. the protected areas sources. Axes show the level of attainment for each objective (%).

In Figure 37 we show the performance of each objective on each of the 18 FS districts for five different weight combinations. If the red or black dots portray large fluctuations in their attainment this means that they are influenced when the weighting scheme is changed, while if they remain at the same levels of attainment, it means that same treated area has the same footprint on this objective no matter how they are arranged on the landscape. In most cases, the protected areas achieved higher attainment (red dots at the right), but there are some cases like the FS district of Korihtnou where community exposure has a better performance (black dots at the right). Notable fluctuations in the attainment were recorded for the FS districs of Kalavryton, Patras and Korithou.

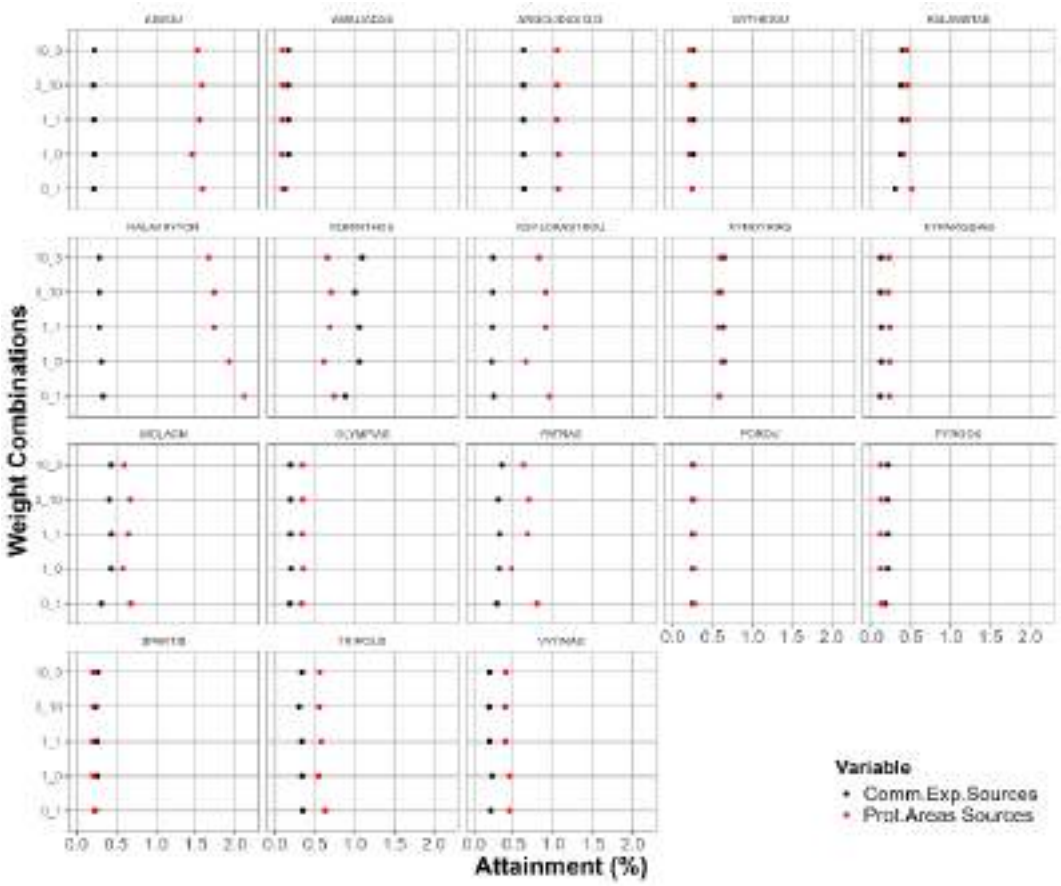

Figure 37 Each panel shows the attainment of each of the two objectives (black: developed areas exposure sources; red: protected areas exposure sources) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Forest Service District.

The second couple examined was the community exposure sources vs. biomass. The map in Figure 38 shows a solution of approximately 41,000 ha for the three examined weight combinations and creates a substantial maximum difference of 1.7% in the attainment of the community exposure sources, and 0.7% for biomass. The overall attainment for the management objective of community exposure sources is approximately 7%, while for the biomass approximately 3.5%. While several of the proposed projects spatially coincide, there are some that differentiate at the FS Vytinas, Olympias, Pyrgou and Kalavryton for the weight combination 10-3 (orange colour), and several in Kyparissia, Patra, Sparti and Olympias for the weight combination 3-10 (blue colour).

The trade-off graph in Figure 39 shows sharp differences for most of the FS districts, especially for Sparti, Kalamata, Tripoli and Kynouria (i.e., the more the attainment of the community exposure sources is increased, the more the biomass is decreased). These curves suggest that there are opportunities for a spatial allocation of projects (i.e., projects from a weight combination at the middle of each curve) that can achieve relatively high attainments for both management objectives. Overall, the attainment capacity of this objective combination is low, since the highest performing FS district like the Korinthou can achieve a maximum of 1.25% attainment for the community exposure sources with approximately 0.2% for biomass, while the highest performing curve for

biomass is in the FS district of Xylokastrou, with approximately 0.3% attainment (and 0.25% for community exposure).

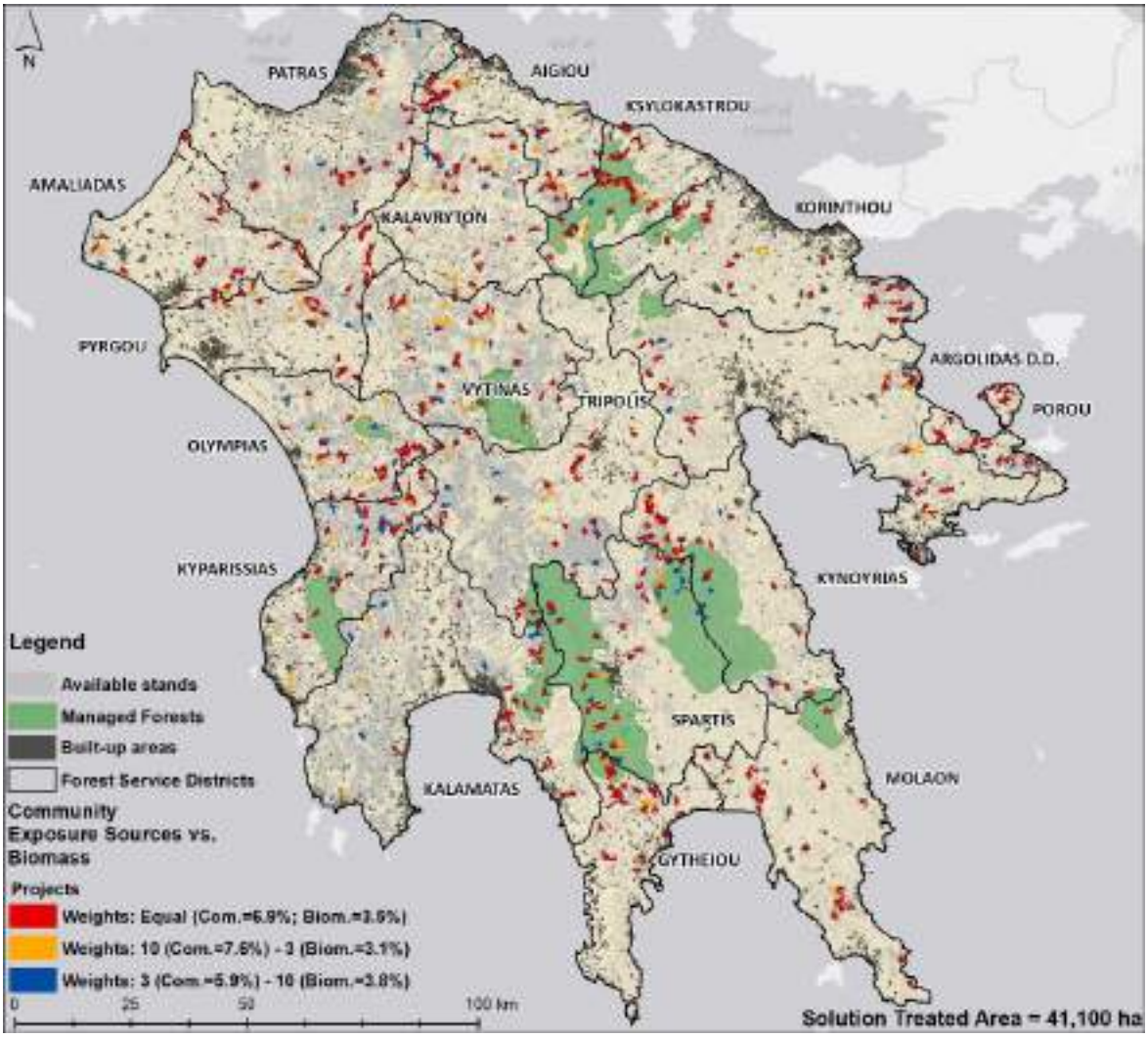

Figure 38 Trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Developed areas exposure sources objective weight maximized (10) and retrieved biomass set to low (3) (orange); c) retrieved biomass objective weight maximized (10) and developed areas exposure sources set to low (3) (blue).

In Figure 40 we noticed large fluctuations in the attainment of the FS districts of Korintou, Kalamatas, Argolidas, Spartis and Tripolis for the community exposure objective. The biomass objective has also fluctuations for some FS districs, like Spartis, Tripolis and Vytinas, but their range in attainment is small. In most cases, the community exposure sources achieved higher attainment (black dots at the right), but there are some cases like the FS district of Aigiou, Pyrgou and Kyparissias where biomass has a better performance (red dots at the right). Compared to the previous couple of objectives, this one has evident trade-offs when the weighting scheme is changed, an evident fact from the appearance of different colours on the map (orange and blue instead of just red), the curved shape of the FS district lines, and the large fluctuations in the dots of the attainment graph.

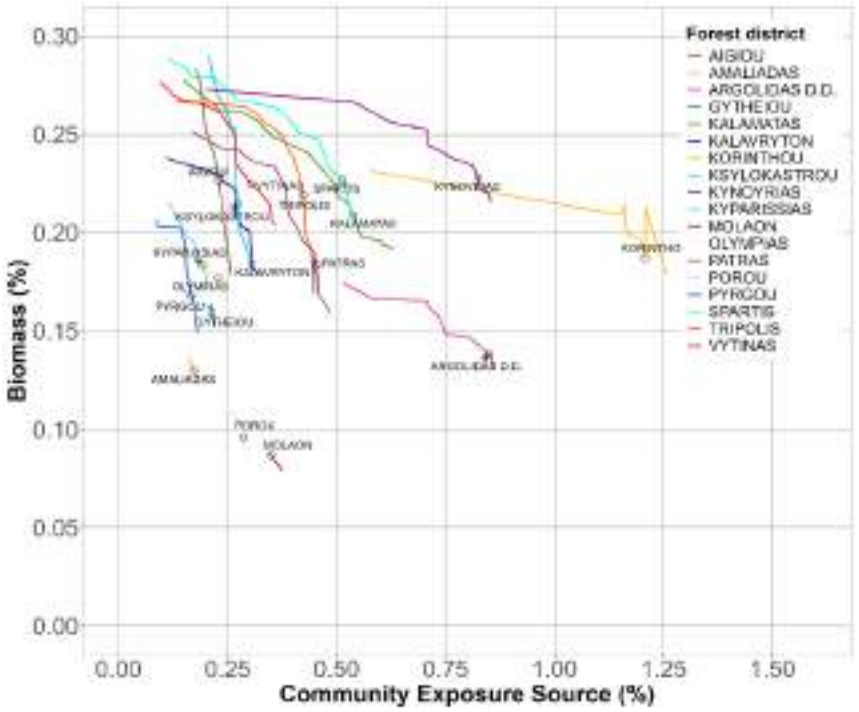

Figure 39 Tradeoff production probability curves for each Forest Service District for the objectives of retrieved biomass vs. developed areas exposure sources. Axes show the level of attainment for each objective (%).

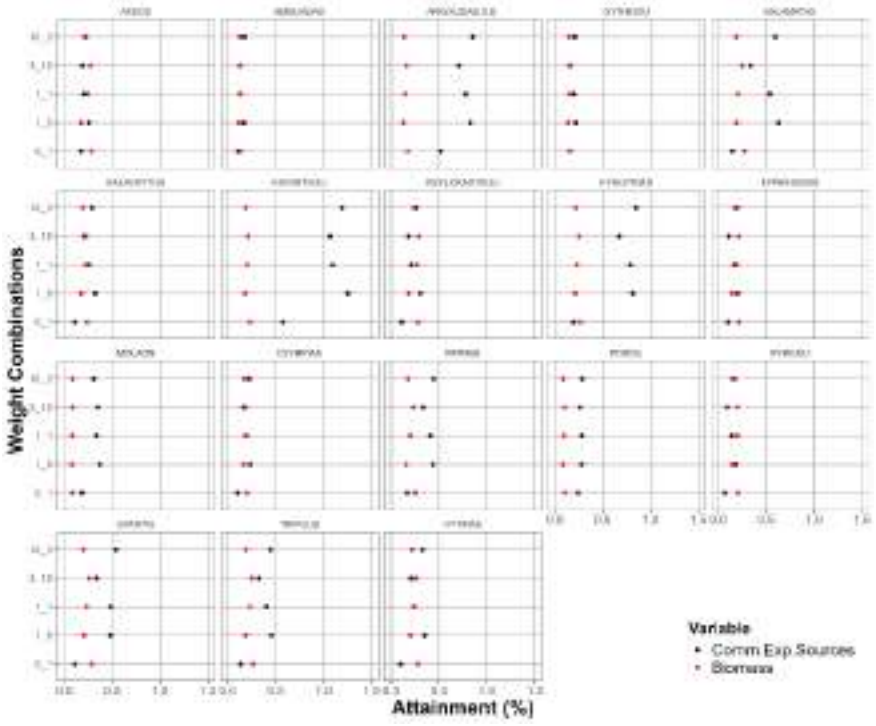

Figure 40 Each panel shows the attainment of each of the two objectives (black: developed areas exposure sources; red: biomass retrieved) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Forest Service District.

The third couple examined the community exposure sources vs. sinks. The map in Figure 41 shows a solution of approximately 34,300 ha for the three examined weight combinations and creates a small maximum difference of 0.5% in the attainment of the community exposure sources, and 0.6% for the sinks. The overall attainment for the management objective of community exposure sources is approximately 4%, while for the sinks approximately 3.2%. While several of the proposed projects spatially coincide, there are some that differentiate at the FS Vytinas, Pyrgou, Kalamatas and Korinthou for the weight combination 10-3 (orange colour), and several in Vytinas, Tripolis, Kalamatas and Spartis for the weight combination 3-10 (blue colour).

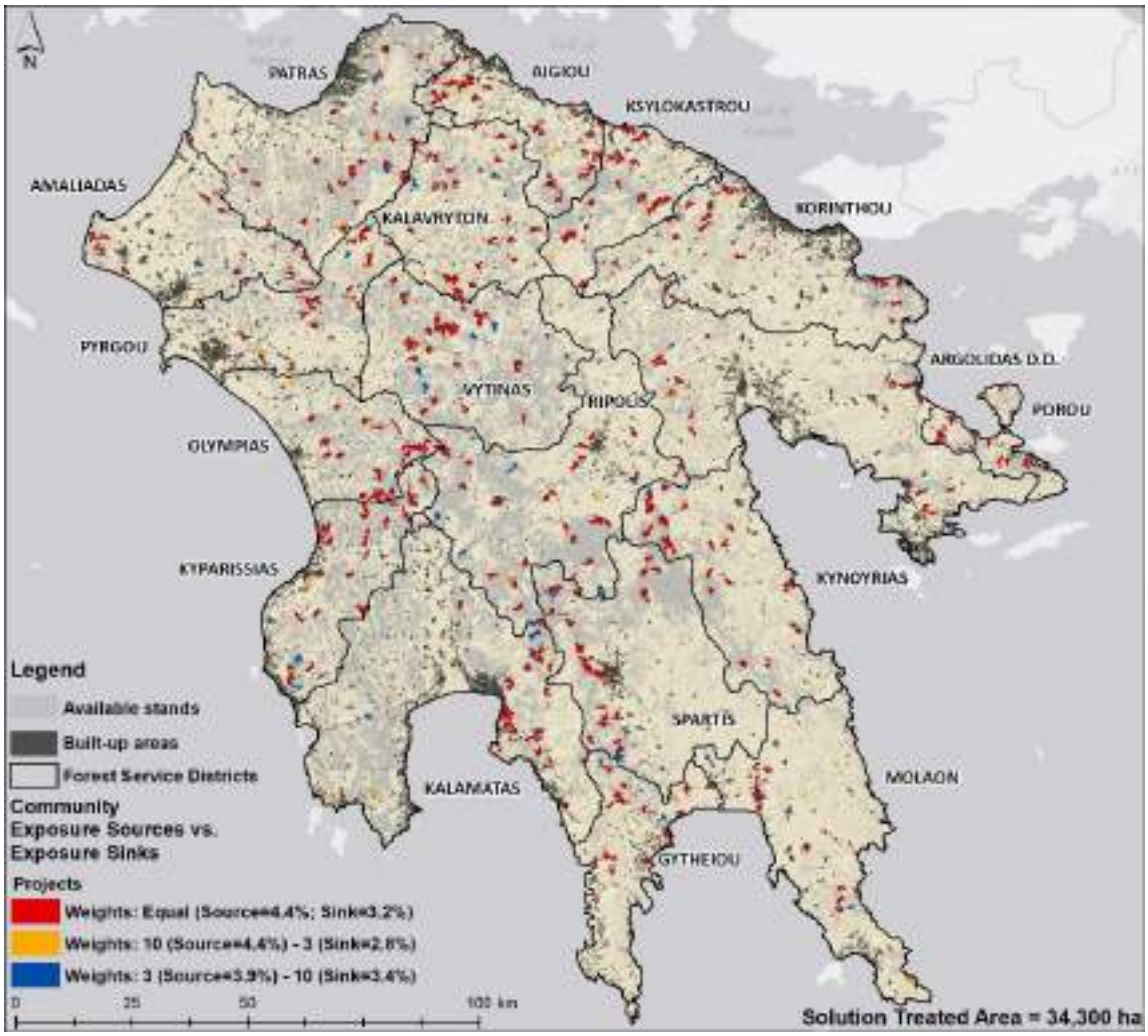

Figure 41 Tradeoff scenario planning runs with three weighting schemes: a) equal weights (red); b) Developed areas exposure sources objective weight maximized (10) and developed areas exposure sinks set to low (3) (orange); c) Developed areas exposure sinks objective weight maximized (10) and developed areas exposure sources set to low (3) (blue).

The trade-off graph in Figure 42 shows sharp differences for most of the FS districts, especially for Korinthou, Argolidas, Molaon and Kalamatas (i.e., the more the attainment of the community sinks is increased, the more the sources is decreased). Overall, the attainment capacity of this objective combination is low, since the highest performing FS district like the Korinthou can achieve a maximum of 0.6% attainment for the community

exposure sources with approximately 0.2% for sinks, while the highest performing curve for community sinks is in the FS district of Kynourias, with approximately 0.5% attainment (and 0.43% for community exposure sources).

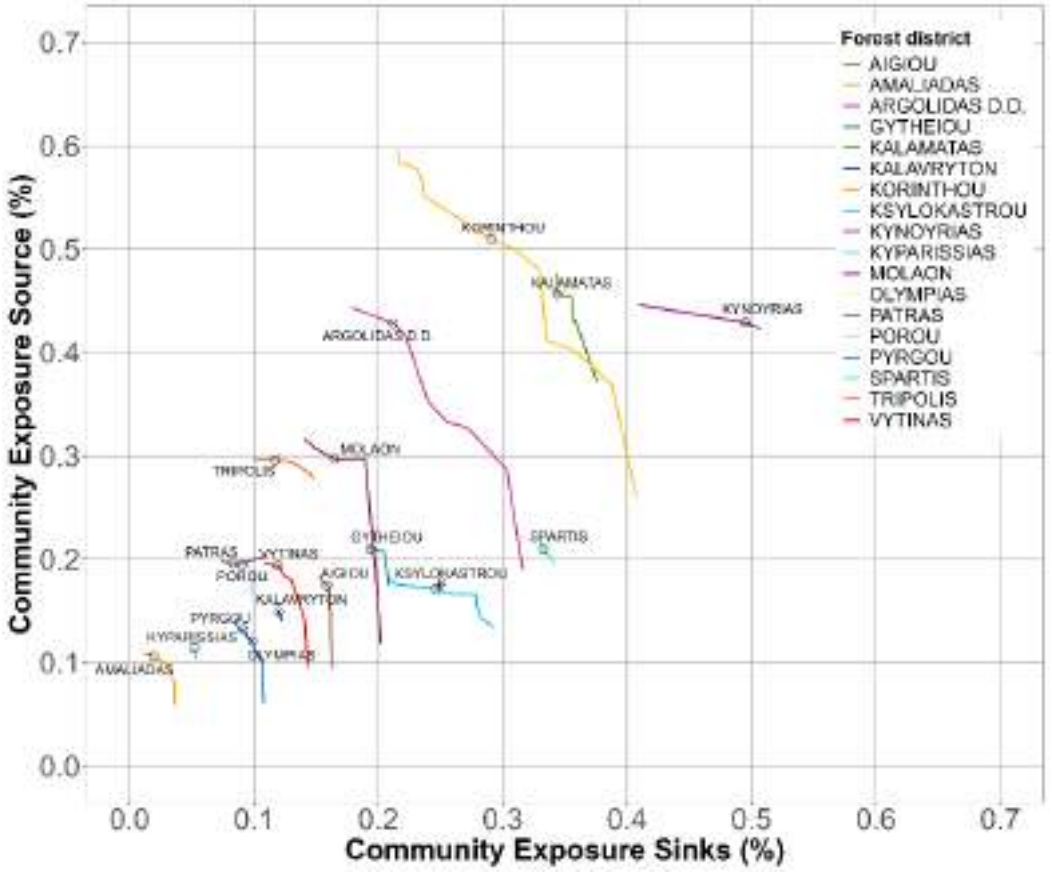

Figure 42 Tradeoff production probability curves for each Forest Service District for the objectives of developed areas exposure sources vs. developed areas exposure sinks. Axes show the level of attainment for each objective (%).

In Figure 43 we noticed large fluctuations in the attainment of almost all the FS districts, with most notable those of Korinthou, Argolidas, Kalamatas, Kynourias and Tripolis. These fluctuations cause in some weight combinations to alternate which objective achieves higher attainment. We also notice fluctuations in the attainment of each objective individually, for example, in Korinthou the combination of 10-3 cause the sources to achieve 0.6% attainment and sinks 0.2%, while the combination 0-1 cause the sources to achieve 0.25% and the sinks 0.4%. Some FS districts, like Porou, Olympias, Kyparissias and Kalavryton have a stable pattern of attainment for both the objectives across all weight combinations. Last, community exposure sinks achieved better attainment for the FS districts of Spartis, Kynourias and Ksylokastrou, meaning that there is more efficient to protect communities close or inside their boundaries compared to the rest of FS districts, where it is more preferable to choose projects from weight combinations that achieved with high attainment for the sources and focus on mitigating fire risk in the locations where large fires initiate and spread into the communities. Here again, this couple has evident trade-offs when the weighting scheme is changed, an evident fact from the appearance of different colours on the map (orange and blue

instead of just red), the curved shape of the FS district lines, and the large fluctuations in the dots of the attainment graph.

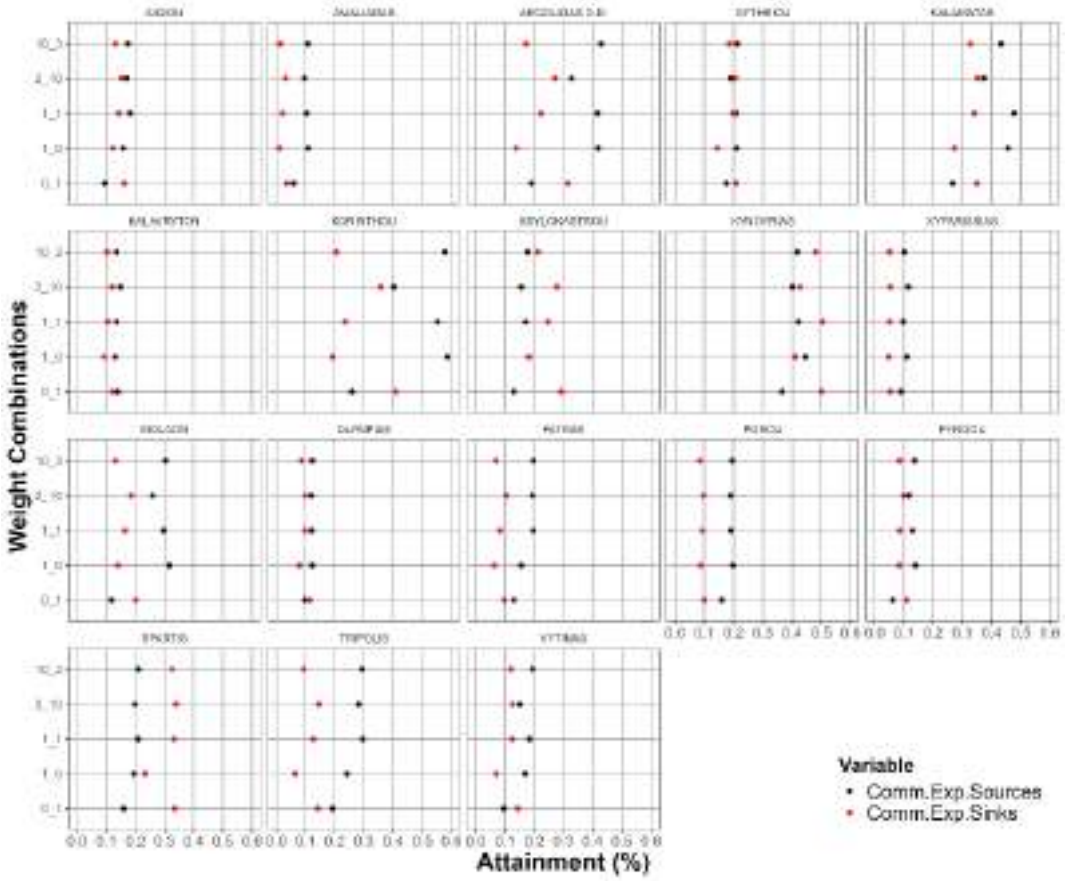

Figure 43 Each panel shows the attainment of each of the two objectives (black: developed areas exposure sources; red: developed areas exposure sinks) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Forest Service District.

The last couple of objectives examines whether it is better to apply fuel treatments on projects inside the protected areas (sinks) or where the fire risk originates (either inside or outside protected areas – sources). The map in Figure 44 shows a solution of approximately 18,500 ha for the three examined weight combinations and creates a minor maximum difference of 0.2% in the attainment of the protected areas exposure sources, and 0.4% for the sinks. The overall attainment for the management objective of protected areas exposure sources is approximately 7%, while for the sinks approximately 12%. The total attainment for both objectives is considered high for the area selected for receiving fuel treatments. Almost all proposed projects spatially coincide, except for some projects inside the FS district of Kalavryton. In Figure 45 we notice only some minor fluctuations in the performance of the FS districts of Aigiou and Kalavryton, but without a clear trade-off curve or pattern. Almost all other FS districts either have unchanged the attainment of one objective while the other increases (e.g., Kynourias, Patras or Argolidas), or have minor and unimportant changes.

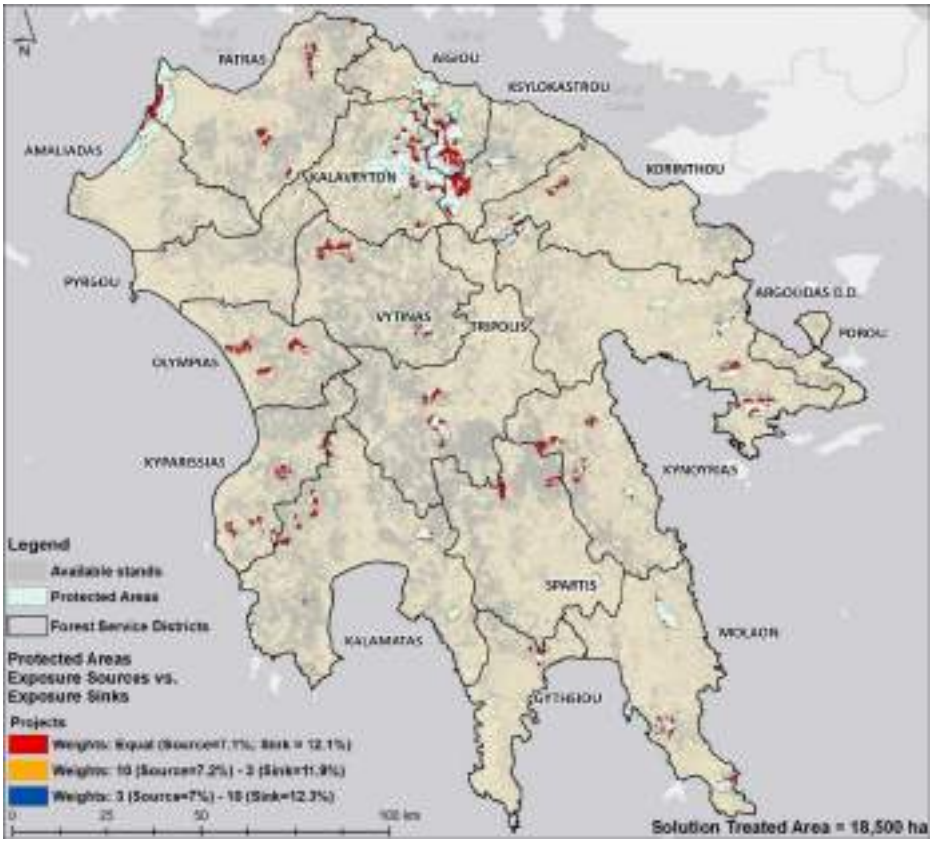

Figure 44 Trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Protected areas exposure sources objective weight maximized (10) and protected areas exposure sinks set to low (3) (orange); c) Protected areas exposure sinks objective weight maximized (10) and protected areas exposure sources set to low (3) (blue).

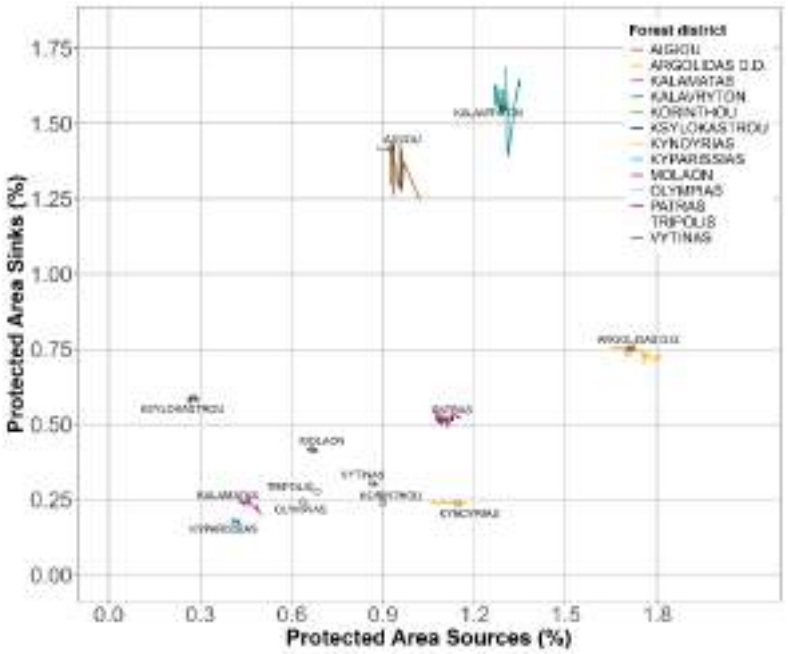

Figure 45 Trade-off production probability curves for each Forest Service District for the objectives of protected areas exposure sources vs. protected areas exposure sinks. Axes show the level of attainment for each objective (%).

In Figure 46 we noticed stable patterns of attainment for each objective and for each FS district. Small fluctuations were found in the attainment of the FS districts of Aigiou and Kalavryton for the objective of protected areas exposure sources, while the FS districts of Kynourias, Argolidas and Aigiou had small attainment changes for the objective of protected areas exposure sinks. This couple of objectives has no evident trade-offs when the weighting scheme is changed, i.e., no appearance of different colours on the map except for red, no curved shaped FS district lines, and minor fluctuations in the dots of the attainment graph.

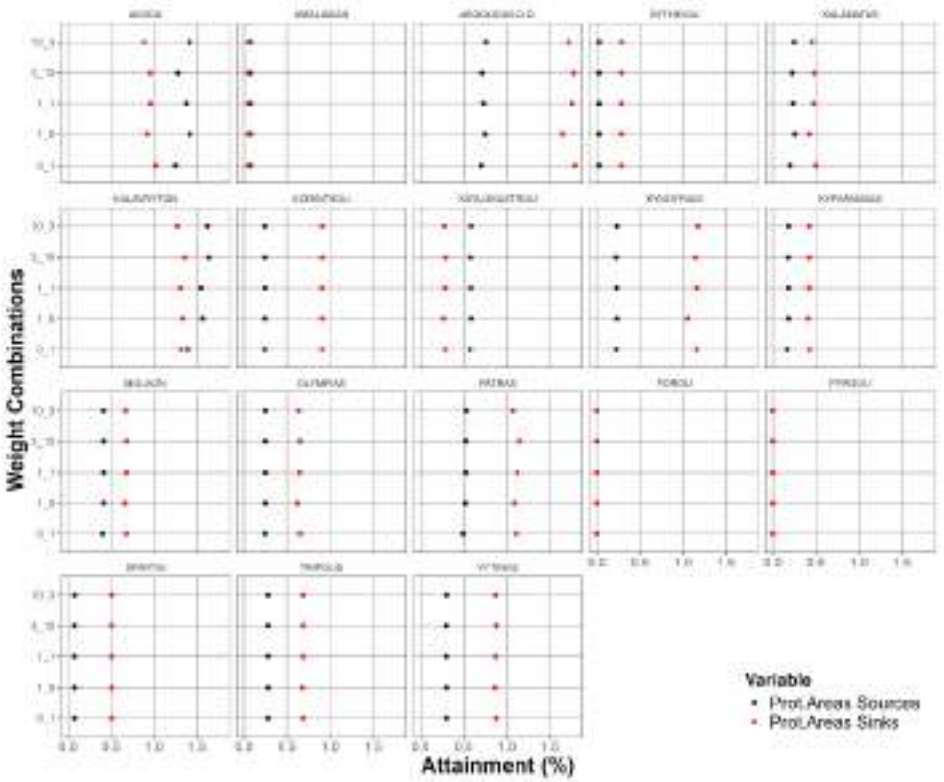

Figure 46 Each panel shows the attainment of each of the two objectives (black: protected areas exposure sources; red: protected areas exposure sinks) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Forest Service District.

4.2 Living Lab Portugal

The region of application for this component in the Living Lab of Portugal is the Vale Do Sousa, a region that cover 1.93 million ha of which, 495,000 ha are available for receiving fuel treatment projects. The analysis was performed at the level of Municipalities (66 in total, with an area ranging from 2,700 ha to 117,000 ha). We analysed the effects of fuel treatment projects at eight management objectives: biomass retrieval, protection of carbon stocks, fire risk reduction at the community exposure sources, protection of community exposure sinks (parts of communities that receive the highest amounts of fire), reduction of fire hazard (i.e., energy release) to facilitate better fire suppression, reduction of future ignitions in high ignition probability areas, reduction of the exposure of protected areas from the sources of their exposure, and protection of the most exposed parts of protected areas (sinks).

4.2.1 SET0: Control & Evaluation

In this set of fuel treatment scenario planning, we estimated the effect that spatial optimization has in three management objectives, namely community exposure sources, protected exposure sources and ignition probability, when we select to apply fuel treatments at approximately 20,000 ha and we compared with a random and a proximity to roads allocation schemes. We found that both random and roads allocation have very low performance when compared with the optimized allocation (Figure 47). In particular, the optimized allocation for protected areas exposure sources can achieve an attainment of up to 7% compared to the 1% the non-optimized allocation achieved, the community exposure sources optimized allocation achieved approximately 8% vs. the 1% of the non-optimized allocation, and finally, we found smaller differences between the spatially optimized allocation of the reduction of ignition probability that achieved approximately 3% attainment vs. the 1.5% of the non-optimized allocations. These results prove that the business-as-usual way of allocating fuel treatment projects (i.e., randomly or in proximity to roads) cannot provide substantial reduction to key management objectives like the protection of communities or risk reduction for protected areas and can have a similar impact only for the objective of reducing ignition probability.

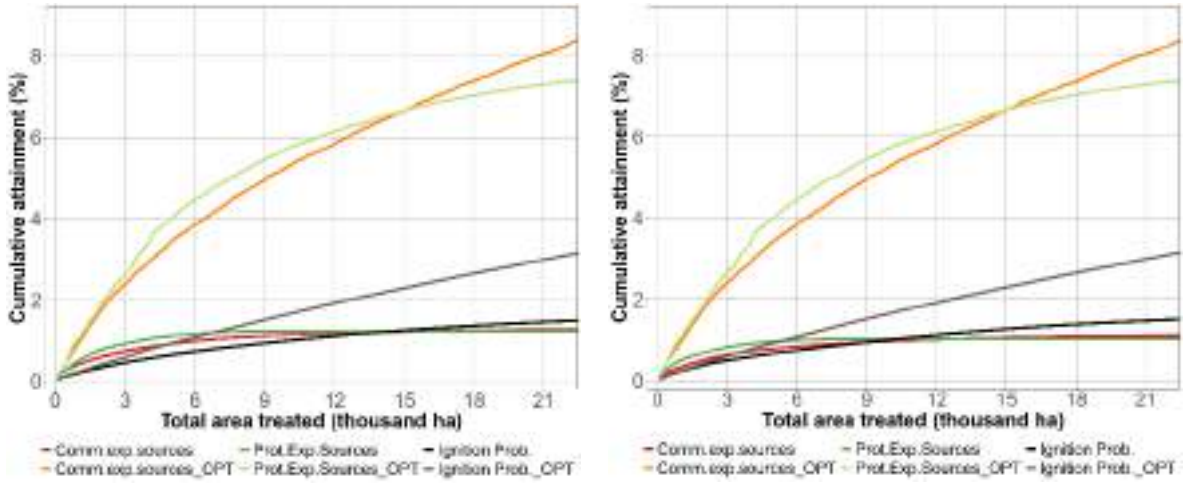

Figure 47 Left: Random project allocation; Right: Project allocation proximate to the road network. OPT: Results from the optimization runs. For comparison, similar colours with different intensity were used for the same objective.

4.2.2 SET1: Efficiency, with a 10-year implementation plan

The implementation of a 10-year plan to reduce the fire risk of the communities from the sources of their exposure by treating half (i.e., 110,000 ha) of the lands that are available for treatment and has a value greater than zero for that objective (i.e., 220,000 ha), resulted to request the spatial optimization of 1100 projects (Figure 48).

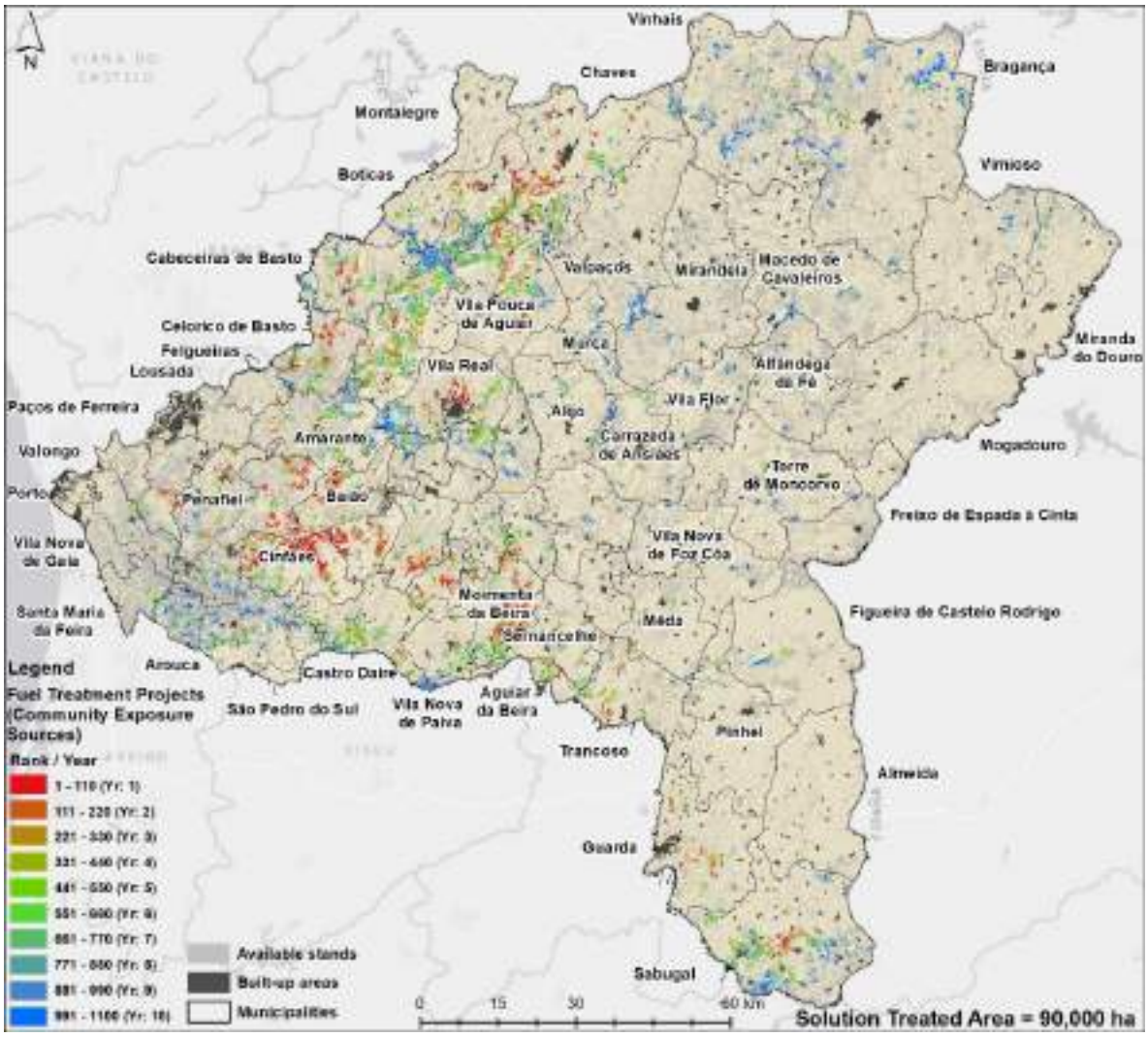

Figure 48 Map of the 1100 projects ranked by the level of attainment they achieve and distributed evenly across each year of the 10-year implementation plan of fuel treatment with the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

The total treated area returned from the spatial optimization solution is 90,000 ha. In this optimization run we did not consider any administrative boundary. Each year, approximately 9,000 ha should be treated (Figure 49), and during the first year the main objective (i.e., community exposure sources) can reach an attainment of up to 5%. For the first five years, the attainment of the main objective can reach 11% by treating approximately 42,000 ha, with the attainment of the other objectives be low (~4%) except for the biomass that is very effective and can reach up to 5% by the fifth year. After the fifth year, the attainment for the main objective is slightly increased to reach ~13% by the tenth year, while the other objectives rise more sharply to reach an attainment of ~10%

for biomass, and ~9% for carbon, with the fire hazard, ignition probability and protected areas exposure sinks and sources end up to an attainment of approximately 6%.The lower attainment when optimizing for the reduction of the main objective is achieved for the community exposure sinks, that barely reaches 4% by the tenth year.

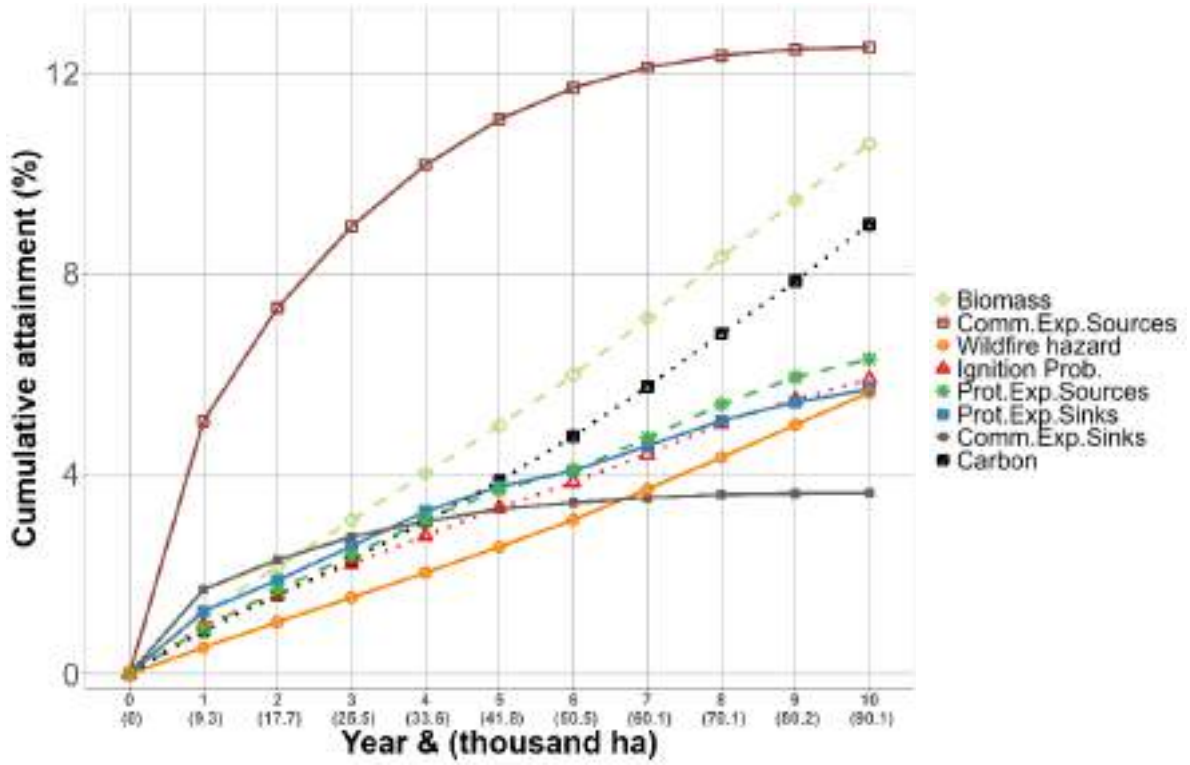

Figure 49 The 10-year implementation plan of fuel treatment with the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

The bulk of the projects are in the Munic. of Sabugal (~5k ha), followed by Ribeira de Pena & Chaves (~4.5k ha), Vila Pouca de Aguiar and Bragança (~4.2k ha), with the remaining Municipalities receiving less than 4k ha of fuel treatments during the 10-year implementation plan (Figure 50-top). The highest attainment is achieved in the Munic. of Cinfães (~2%), although the total treated area is much lower (~4k ha) compared to the other Municipalities (e.g., Sabugal with ~5k ha achieves ~0.4%). It is notable that the projects planned to be implemented during the first year and are in the Municipalities of Cinfães, Resende, Baião, Marco de Canaveses, Vila Real and Celorico de Basto achieve at least half of their total attainment (Figure 50-bottom). This finding suggests that they should be among the first to receive fuel treatments to faster achieving the goals of the main objective.

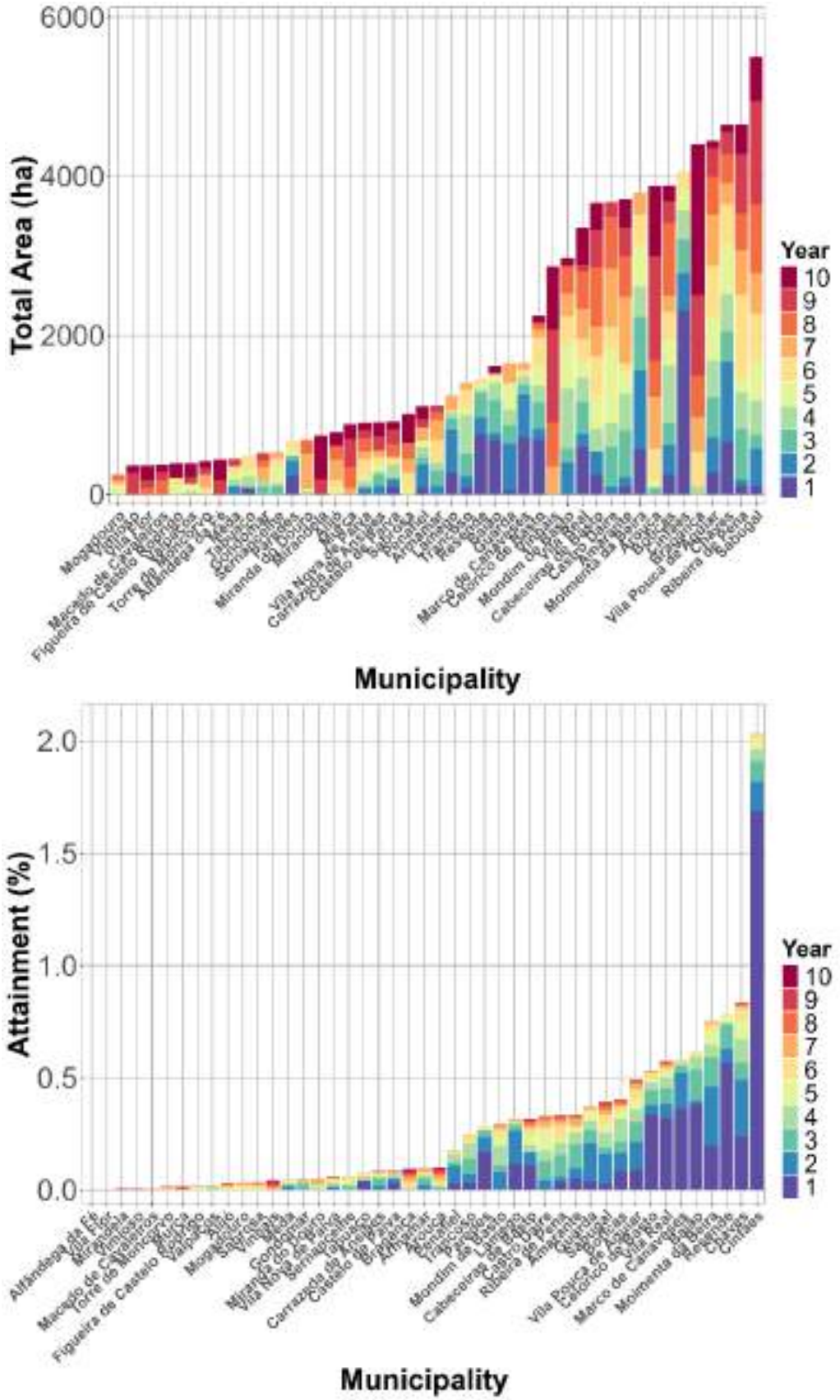

Figure 50 Top: area treated in ha for each Municipality by implementation year. Bottom: main prioritized objective attainment (%) for each Municipality by implementation year.

The implementation of a 10-year plan to reduce the fire risk of the protected areas from the sources of their exposure by treating half (i.e., 32,500 ha) of the lands that are available for treatment and has a value greater than zero for that objective (i.e., 65,000 ha), resulted to request the spatial optimization of 330 projects (Figure 52). The total treated area returned from the spatial optimization solution is 27,100 ha. In this optimization run we did not consider any administrative boundary. Each year, approximately 2,500 ha should be treated (Figure 51), and during the first year the main objective (i.e., protected areas exposure sources) can reach an attainment of up to 2.5%. For the first five years, the attainment of the main objective can reach 6% by treating approximately 13,000 ha, with the attainment of the other objectives be low (<2%) except for the protected areas exposure sinks that is effective and can reach up to 4.5% by the fifth year. After the fifth year, the attainment for the main objective is slightly increased to reach approximately 8% by the tenth year, while the other objectives rise very low to reach an attainment of ~3% for carbon and biomass, and ~2% for the fire hazard, ignition probability and community exposure sources. The lower attainment when optimizing for the reduction of the main objective is achieved for the community exposure sinks, that barely reaches 1% by the tenth year.

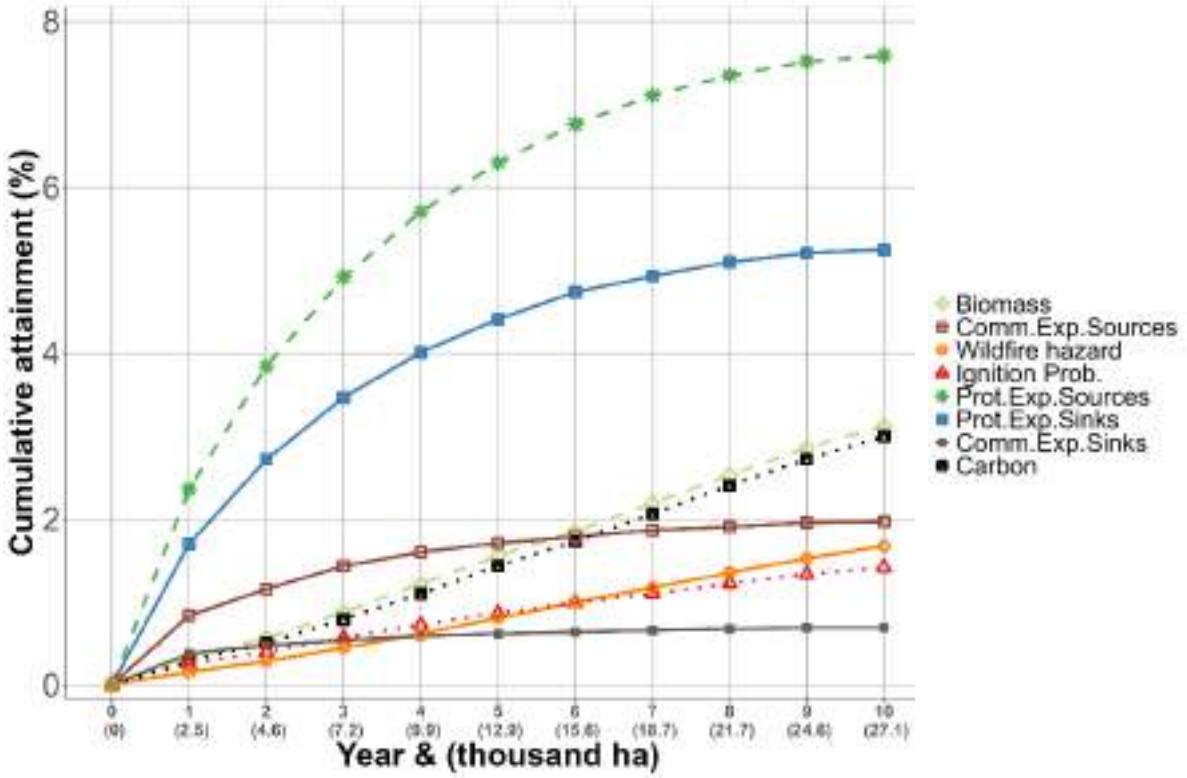

Figure 51 The 10-year implementation plan of fuel treatment with the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

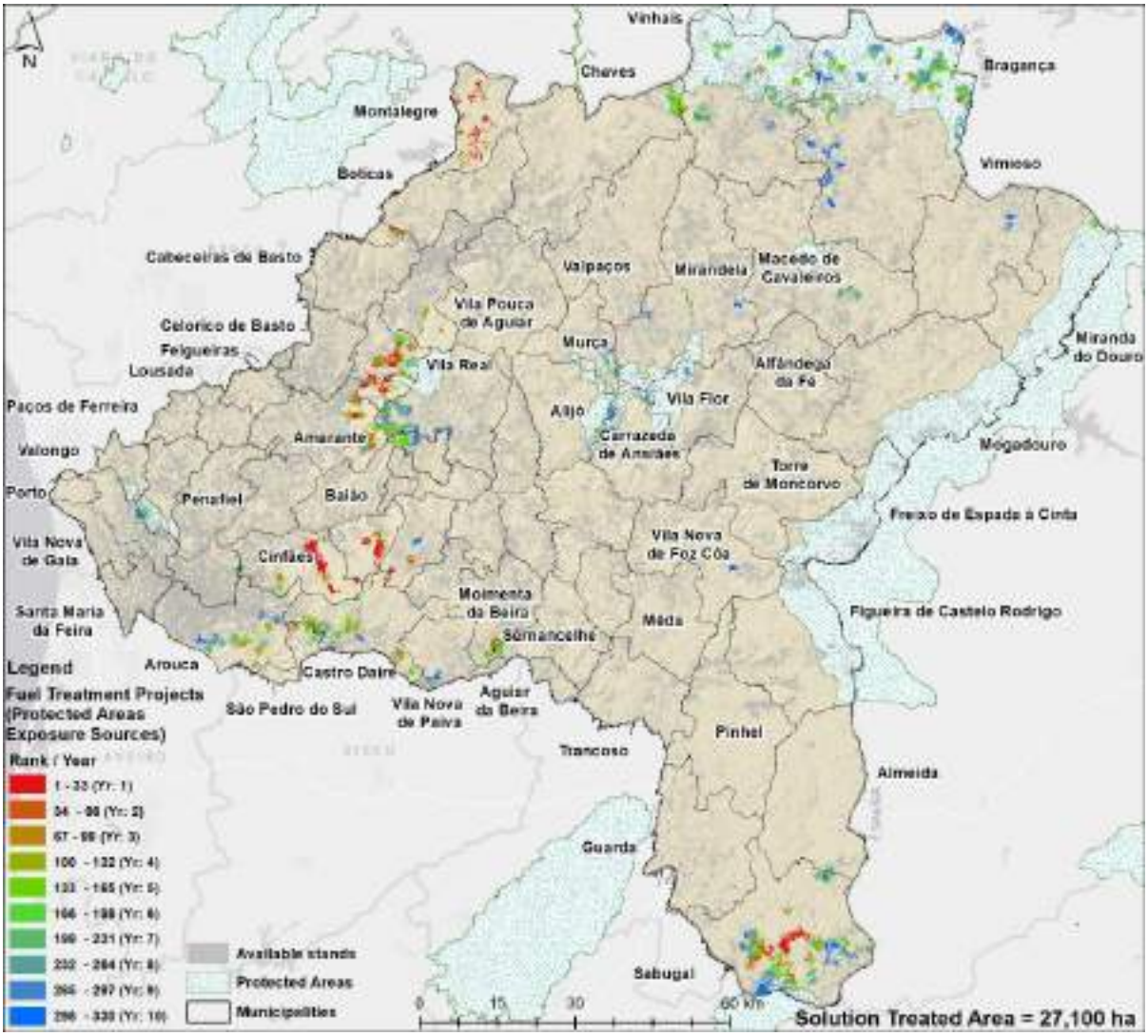

Figure 52 Map of the 330 projects ranked by the level of attainment they achieve and distributed evenly across each year of the 10-year implementation plan of fuel treatment with the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

The bulk of the projects are in the Municipalities of Sabugal and Bragança (~5k ha), followed with much lower treated areas by Mondim de Basto and Vinhais (~2k ha), Castro Daire (1.5k ha), Amarante, Arouca and Cinfães (~1.25k ha), while the remaining Municipalities receive less than 1k ha of fuel treatments during the 10-year implementation plan (Figure 53-top). The highest attainment is achieved in the Municipality of Sabugal (~1.3%), Montalegre and Mondim de Basto (~1%), although the total treated area is much lower for Montalegre (800 ha) and Mondim de Basto (~2.1k ha) compared to the other Municipalities (e.g., Bragança with 5k ha achieves ~0.7%). It is notable that the projects planned to be implemented during the first two years and are in the Municipalities of Sabugal, Montalegre, Mondim de Basto, Cinfães and Resende achieve more than two thirds of their total attainment (Figure 53-bottom). This finding suggests that they should be among the first to receive fuel treatments to faster achieving the goals of the main objective.

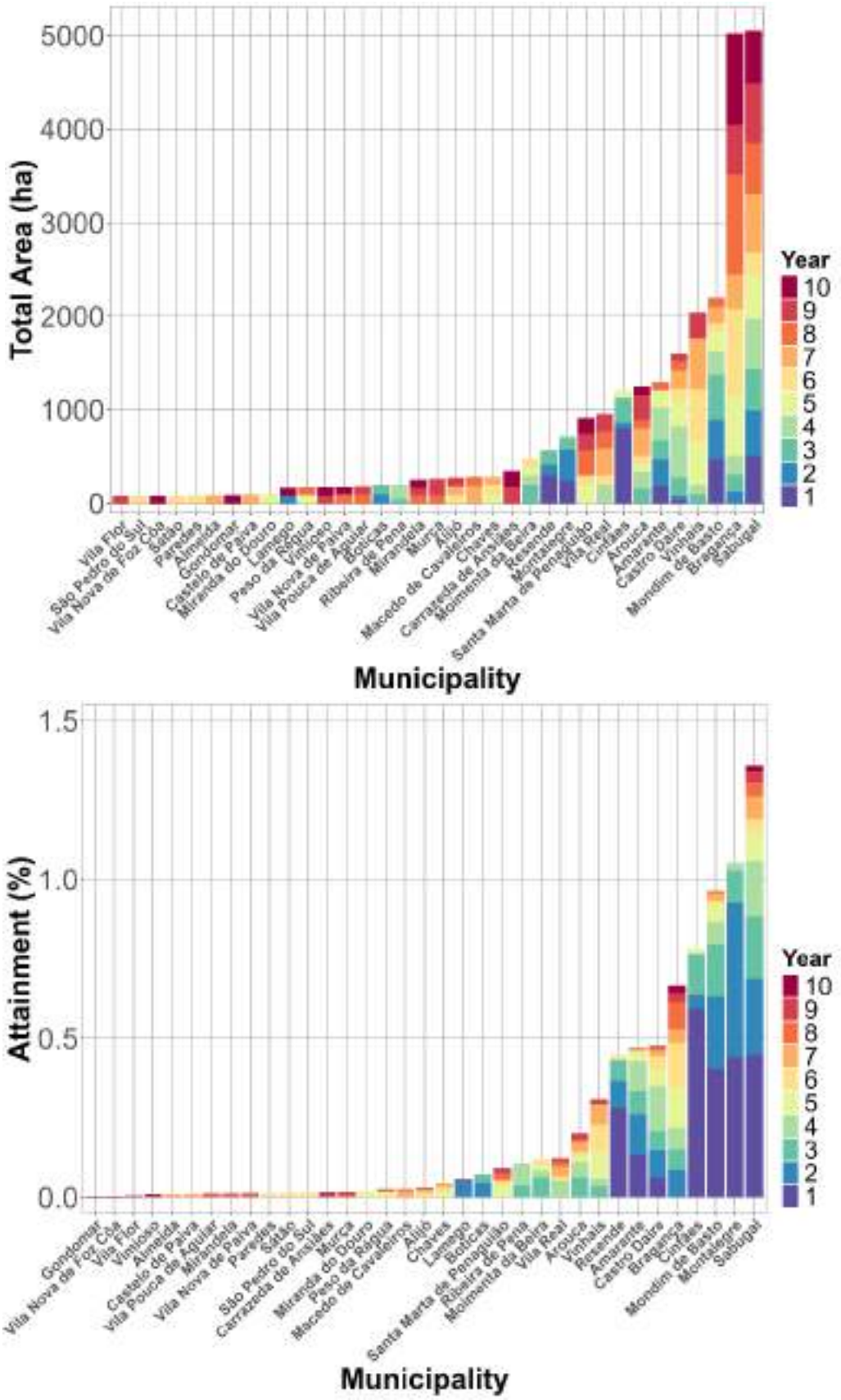

Figure 53 Top: area treated in ha for each Municipality district by implementation year. Bottom: main prioritized objective attainment (%) for each Municipality by implementation year.

The implementation of a 10-year plan to reduce the ignition probability by treating half (i.e., 250,000 ha) of the lands that are available for treatment and has a value greater than zero for that objective (i.e., ~500,000 ha), resulted to request the spatial optimization of 2500 projects (Figure 55). The total treated area returned from the spatial optimization solution is 236,000 ha. The proposed area for treatments is large since all the available stands had an ignition probability value attached that was greater than zero (the unavailable and non-burnable stands were already excluded). In this optimization run we did not consider any administrative boundary. Each year, approximately 24,000 ha should be treated (Figure 54), and during the first year the main objective (i.e., reduction of ignition probability) can reach an attainment of up to 3.5%. For the first five years, the attainment of the main objective can reach ~10% by treating ~120,000 ha, with the highest attainment found for the biomass objective (14.5%). The attainment of carbon is like the main objective (~10%), while for community exposure sources and wildfire hazard is ~7%, for the protected areas sources and sinks approximately 5%, and the community exposure sinks achieve 3.5% of attainment. After the fifth year, the attainment for the main objective is moderately increased to reach ~15% by the tenth year, while the biomass, carbon and wildfire hazard objectives rise linearly to reach 25%, 21% and 14% of attainment respectively, and the protected areas exposure sources and sinks and end up at about 6%, but after treating a massive area that reaches 236k ha. Community exposure sources can achieve an attainment of up to 11%, while for sinks, only 4%.

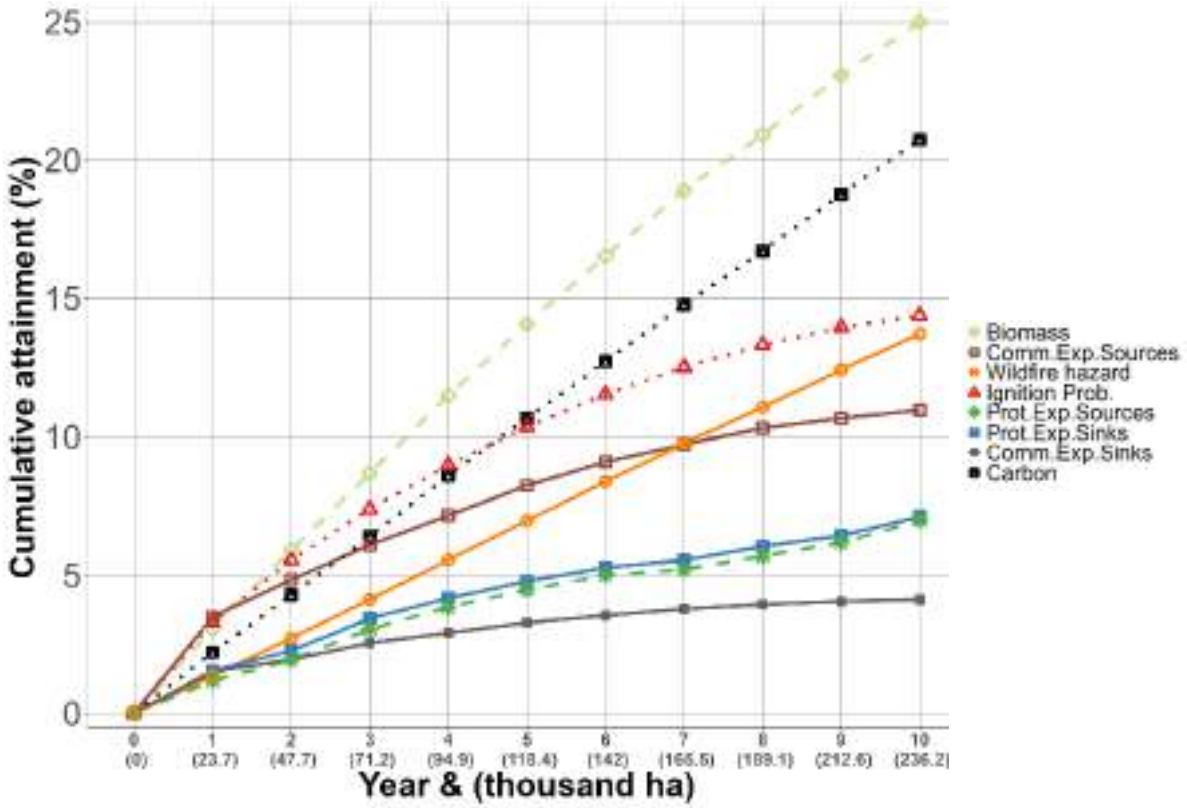

Figure 54 The 10-year implementation plan of fuel treatment with the objective to reduce new ignitions by treated in areas with high ignition probability.

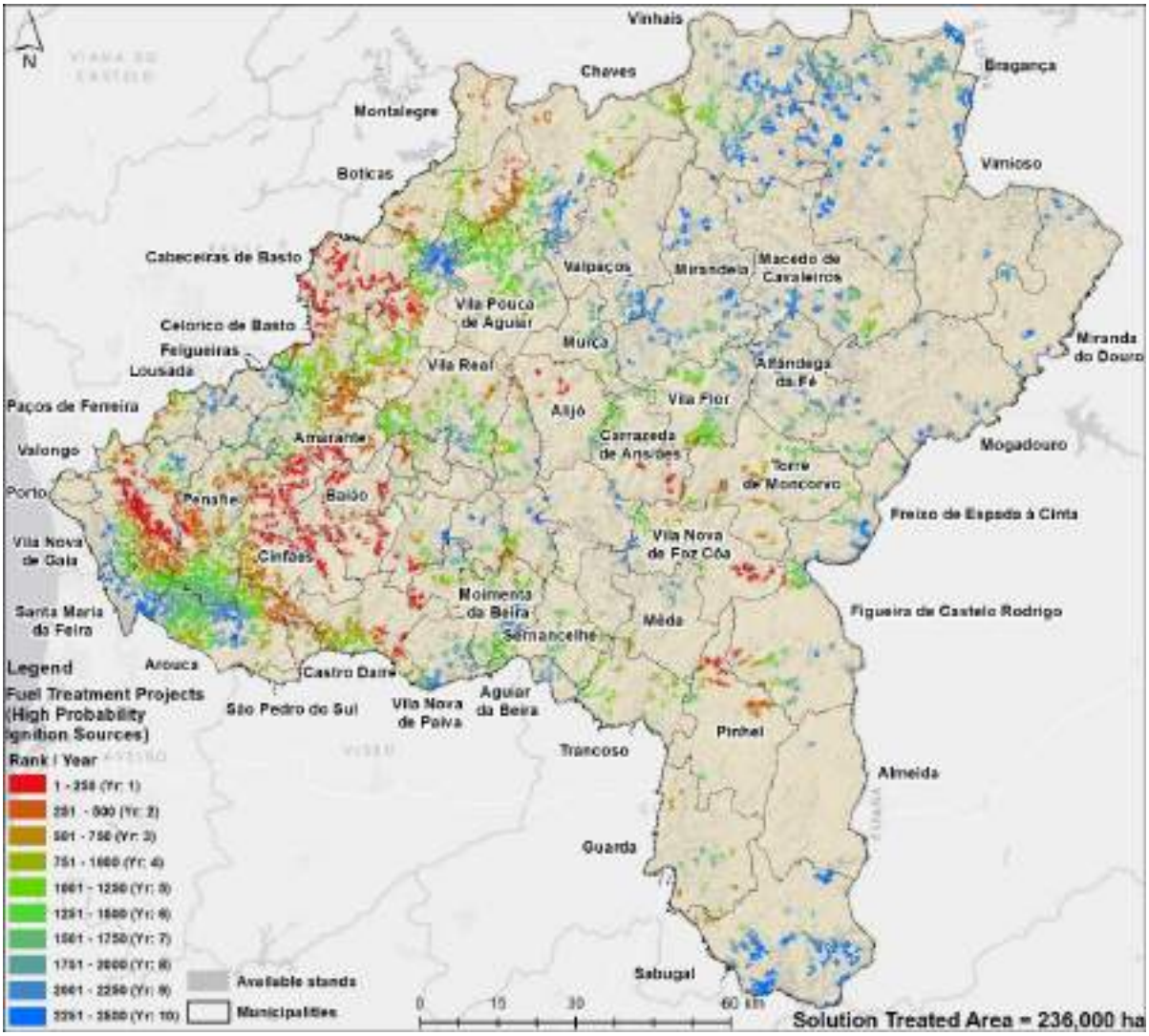

Figure 55 Map of the 2500 projects ranked by the level of attainment they achieve and distributed evenly across each year of the 10-year implementation plan of fuel treatment with the objective to reduce new ignitions by treated in areas with high ignition probability.

The bulk of the projects are in the Municipality of Arouca (~16k ha), followed by Bragança and Boticas (~12k ha), Vila Pouca de Aguiar (11.5k ha) and Chaves (~9.5k ha), with the remaining Municipalities receiving less than 8k ha of fuel treatments during the 10-year implementation plan (Figure 56-top). The by far highest attainment is achieved in the Municipality of Cabeceiras de Basto (~0.9%), that receives a moderate load of treatments (~7k ha), followed by Boticas (0.85%), Arouca (~0.8%), and Marco de Canaveses and Amarante with approximately 0.6% (Figure 56Figure 21-bottom). All other Municipalities achieved attainment <0.6%. The attainment per year is almost evenly distributed among the 10-year period, except for Cabeceiras de Basto, Marco de Canaveses, Cinfães, Gondomar and Baião that achieve at least the two thirds of their total attainment within the first two years of the plan.

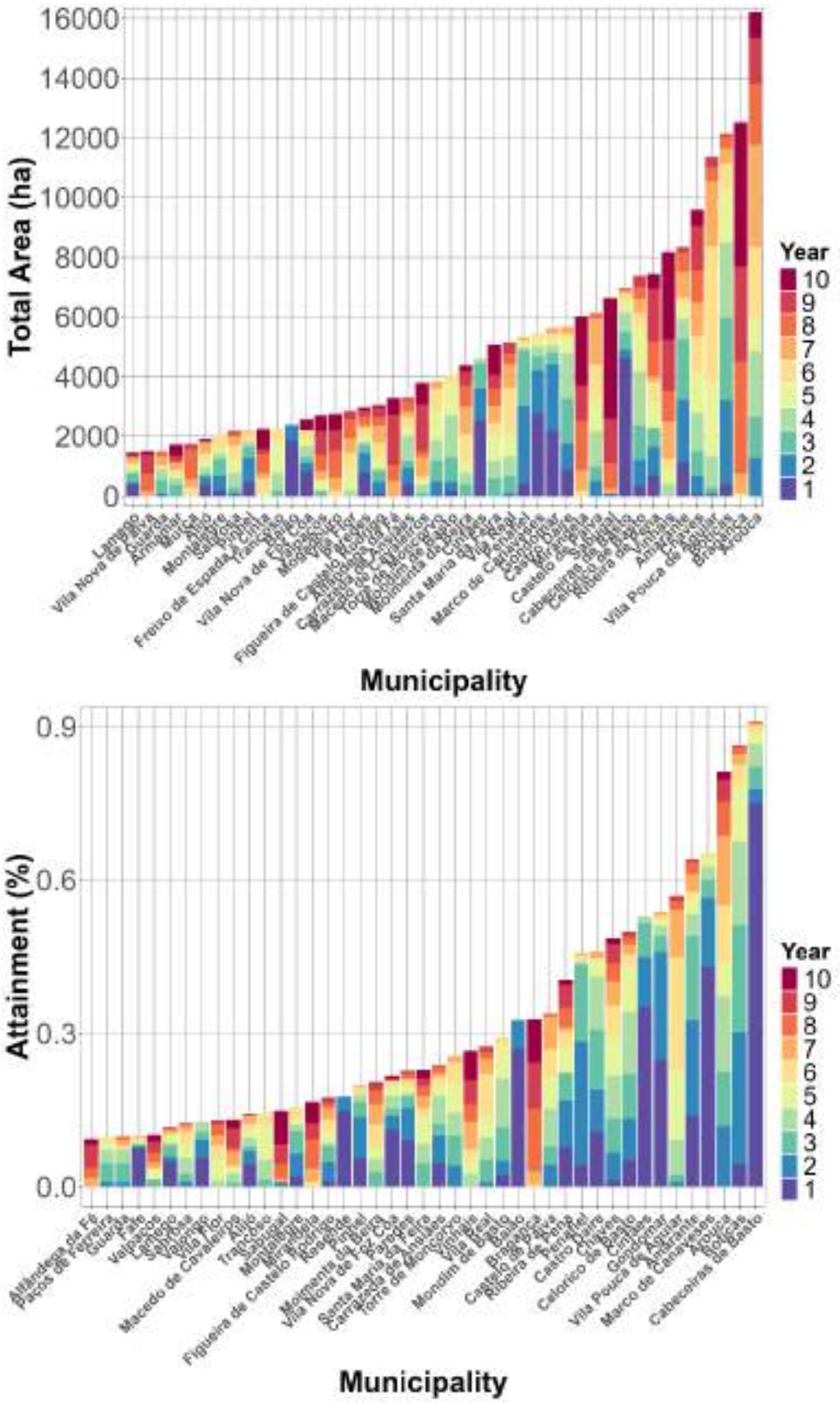

Figure 56 Top: area treated in ha for each Municipality by implementation year. Bottom: main prioritized objective attainment (%) for each Municipality by implementation year.

There are about 80k ha of stands that meet at least two of the three main objectives examined above (community exposure sources, protected areas exposure sources and ignition probability), and ~15k ha of stands that meet all three objectives (Figure 57). For the analysis, these stands are not grouped in projects. When we start selecting these stands that were part of the ForSys solutions for the three main objectives based on the best available stands for the objective of community exposure sources, we notice that by treating approximately half of the area (40k ha) we can achieve a 8% for that objective, ~5% for the protected areas exposure sources, and 3% for the ignition probability (Figure 57-left). By selecting with the same way, the stands that meet all three criteria, an attainment of community exposure sources of ~1.2% is achieved if we treat 15k ha, achieving a ~4% attainment for the protected areas sources and ~1% for the ignition probability (Figure 57-right). By treating the same amount of area (15k ha), we achieve larger attainments in the relevant optimization runs, i.e., 7% vs. 1% for community exposure sources, 4% vs. 6.5% for protected areas exposure sources, and 3% vs. 1% for the ignition probability. In Figure 58 we present all stands that met either more than two (orange) and three (red) objectives.

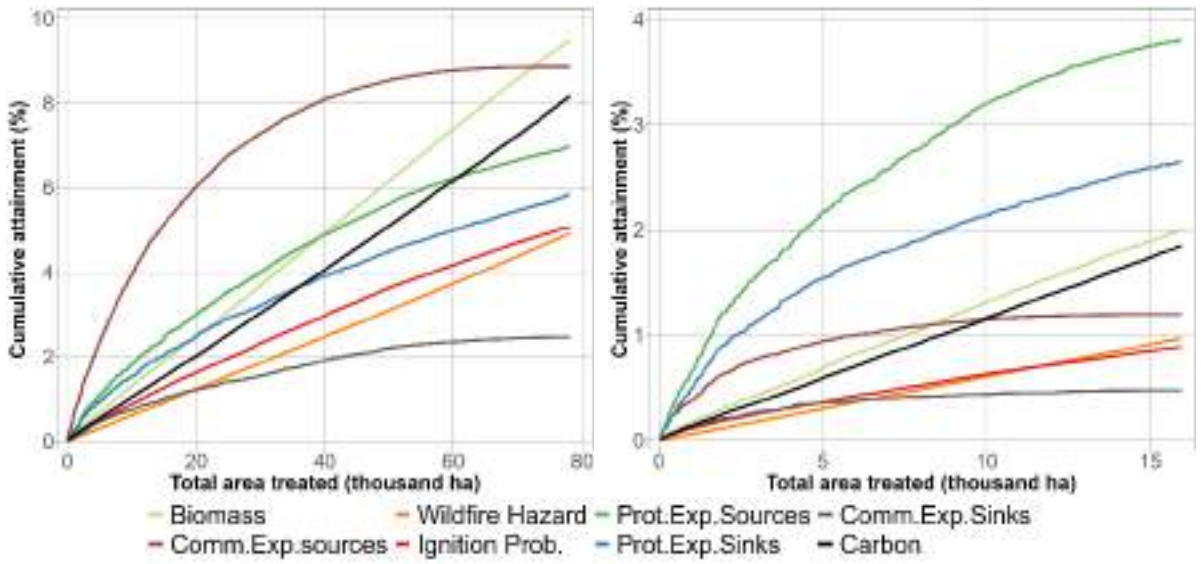

Figure 57 The attainment of the eight objectives analysed for the stands that were selected from the three runs of SET1 that a) meet two or more objectives (left) and b) meet three objectives (right). For graphing purposes, the stands selected first had the highest performance for the objective of community exposure sources.

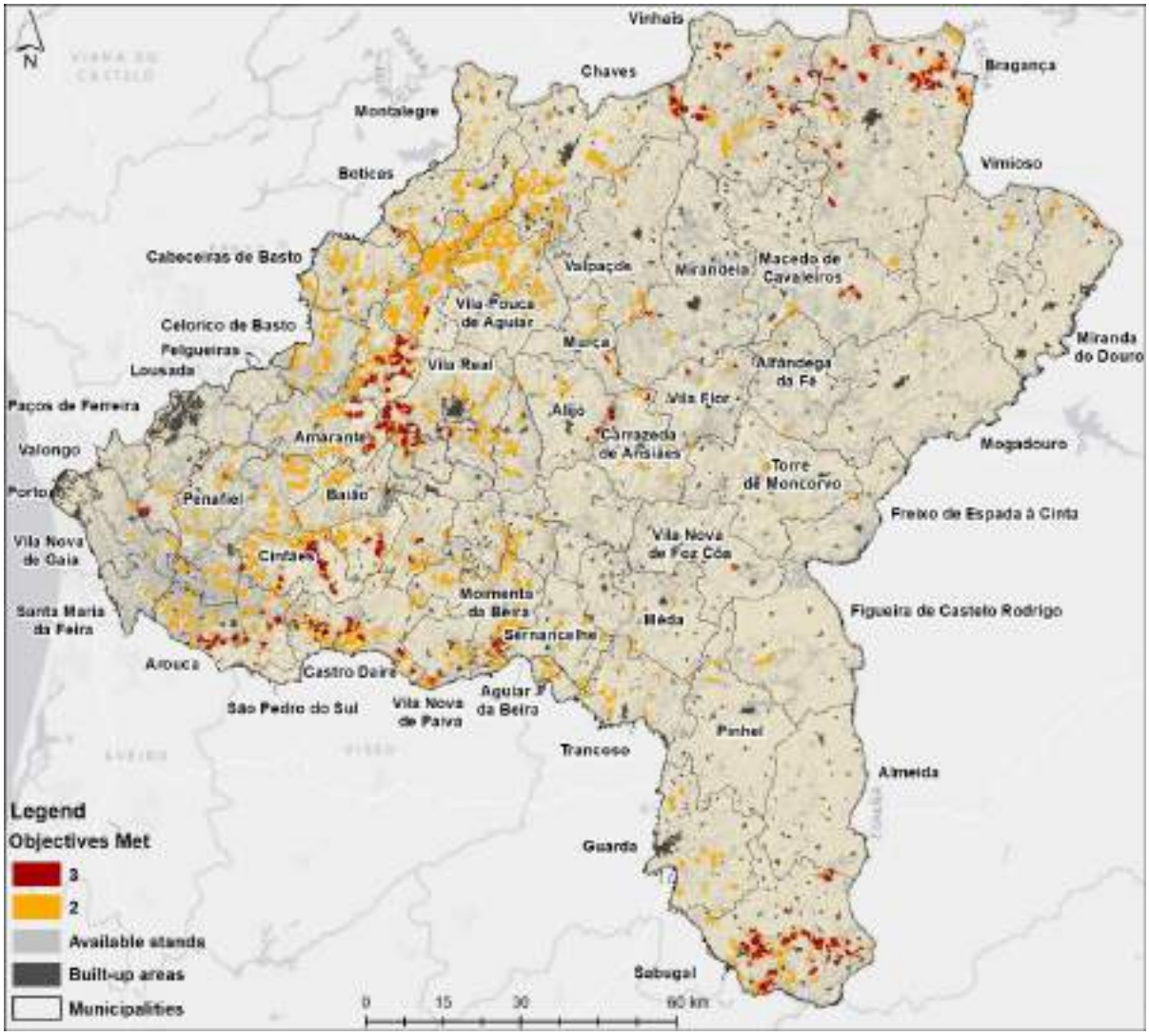

Figure 58 Allocation of stands that were selected from the three runs of SET1 that meet two or more objectives (orange) and three objectives (red).

4.2.3 SET2: Equity among planning areas

In this set of runs we chose to apply an equity approach among the different Municipalities, meaning that we requested the same number of projects for each Municipality with the same treated area. This set does not offer a 10-year management plan. ForSys, given that there are enough available stands, will return what was requested regardless of the area of each district (a district with 50k ha can potentially receive the same projects and area treated as one with 10k ha area). In Figure 59 the attainment curve of community exposure sources can achieve up to ~15% when all the solution area is treated (119,000 ha), with protected areas exposure sources and ignition probability objectives achieving a roughly ~8% and ~7% attainment, respectively. Biomass and Carbon are completely correlated and achieve a 13% and 11% attainment, with smaller attainment for the other four management objectives (~7% or less). In Figure 60 we mapped the 50 projects of each Municipality, with warmer colours applied to the best performing projects when prioritized for the objective of community exposure sources.

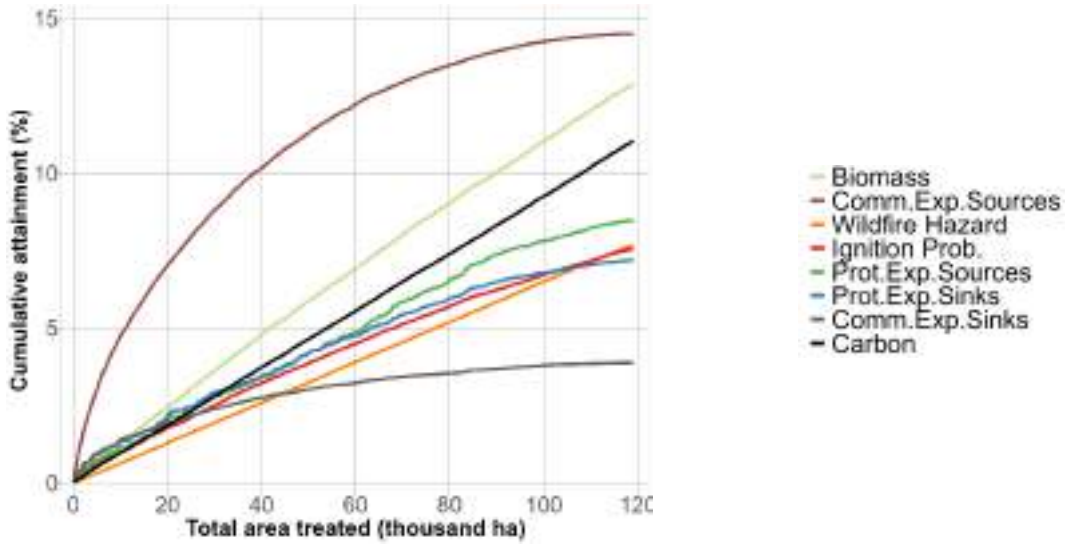

Figure 59 Area treated for all Municipalities and the level of attainment for all objectives after prioritizing for the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

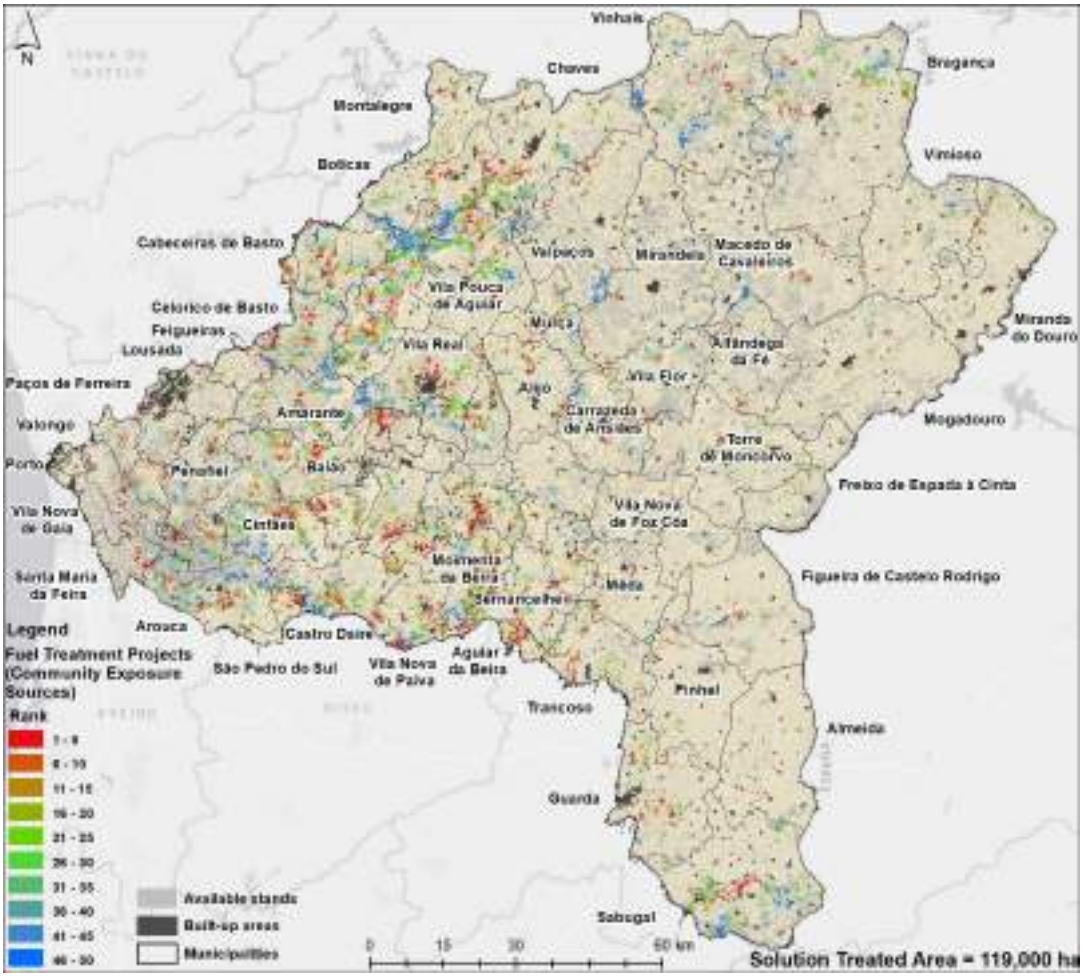

Figure 60 Map of the 50 best projects of each Municipality, ranked by the level of attainment they achieve, with the objective to reduce the exposure of developed areas from incoming wildfires (exposure sources).

The Municipality with the highest attainment for the main objective (community exposure sources) is Cinfães with ~1.7%, followed by Moimenta da Beira and Resende (~0.8%), Chaves, Marco de Canaveses and Baião (~0.6%(with the remaining Municipalities achieving < 0.5% attainment (Figure 61). Except for the two objectives that deal with the protected areas, where we notice that some Municipalities are performing highly although not doing well with the main objective (i.e., Mondim de Basto, Sabugal, Castro Daire and others), all other management objectives achieved low attainment that is <0.5%.

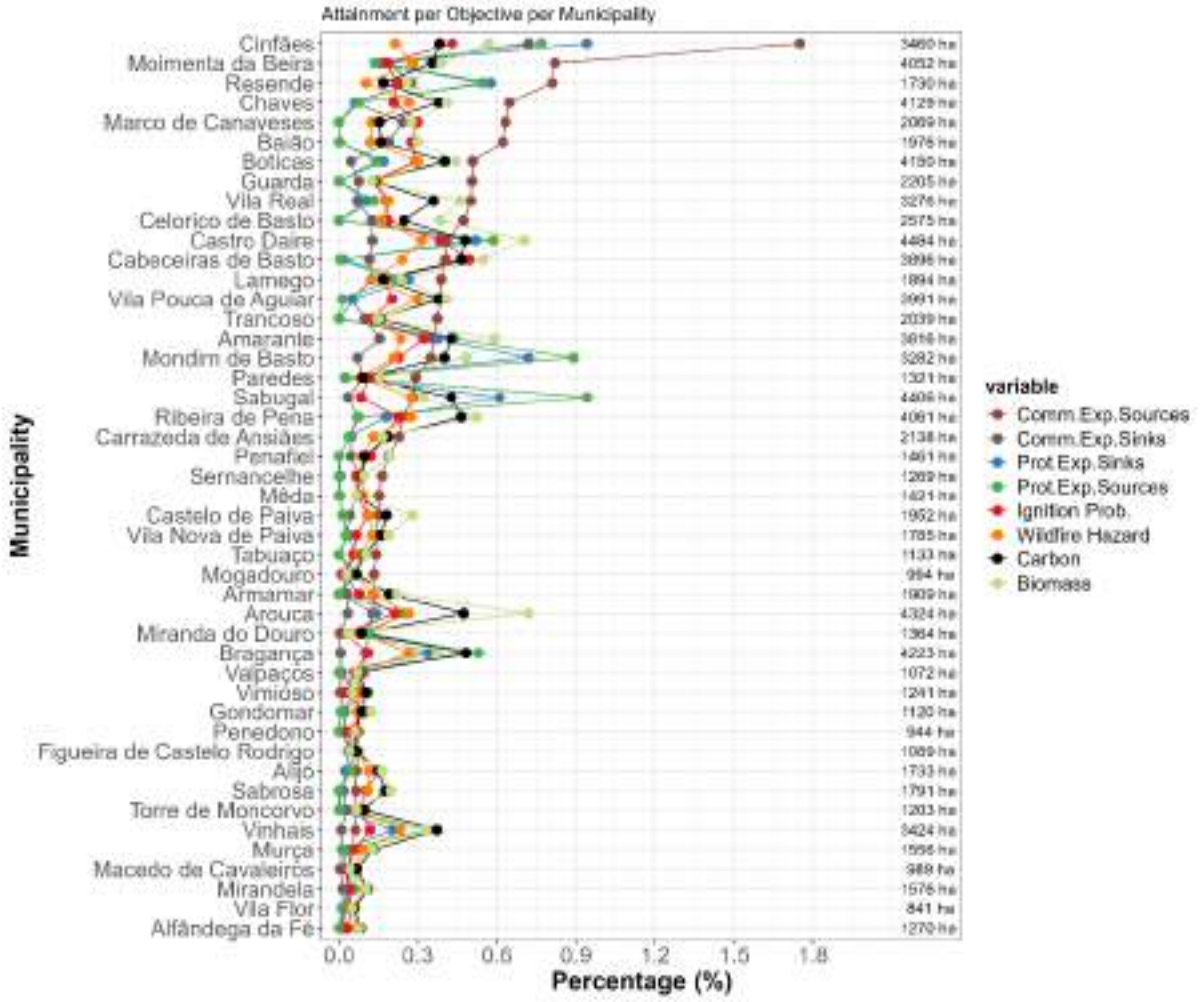

Figure 61 Attainment for each Municipality for the eight objectives when prioritized to reduce the exposure of developed areas from incoming wildfires (exposure sources).

The second run for this set prioritized fuel treatments for the management objective of limiting the exposure from the protected areas sources. In Figure 63 the attainment curve of the main objective can achieve up to ~11% when all the solution area is treated (45,520 ha), with community exposure sources and ignition probability achieving a roughly ~3% attainment. Protected areas exposure sinks achieved a high attainment of about 7%, while carbon and biomass reached approximately 4%. In Figure 62 we noticed that the projects are, as expected, clustered around the protected areas, with 13 Municipalities receiving less than 20 projects, either due to their small area (Vieira do Minho) or because there were no protected areas in proximity to or inside their boundaries or the available

for treatment stands did not contributed enough to their exposure (Valpaços and Guarda).

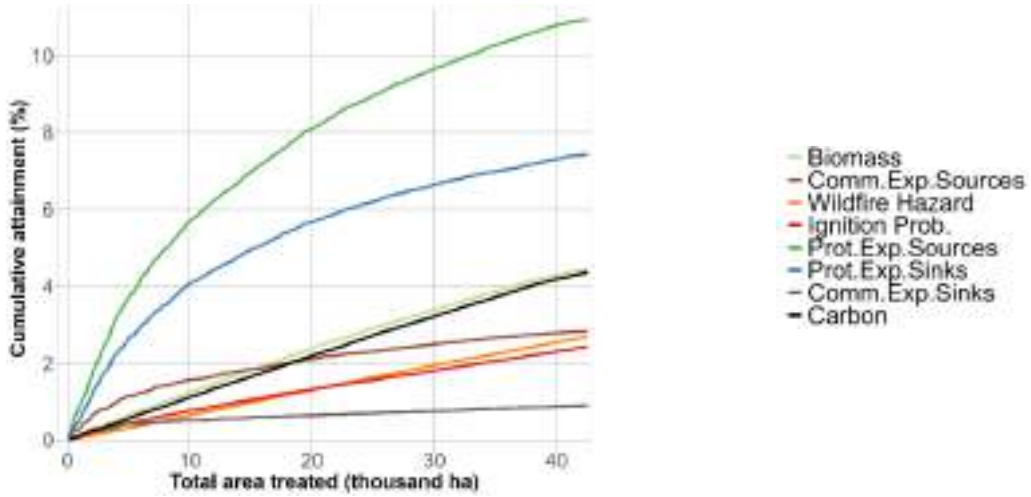

Figure 62. Area treated for all Municipalities and the level of attainment for all objectives after prioritizing for the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

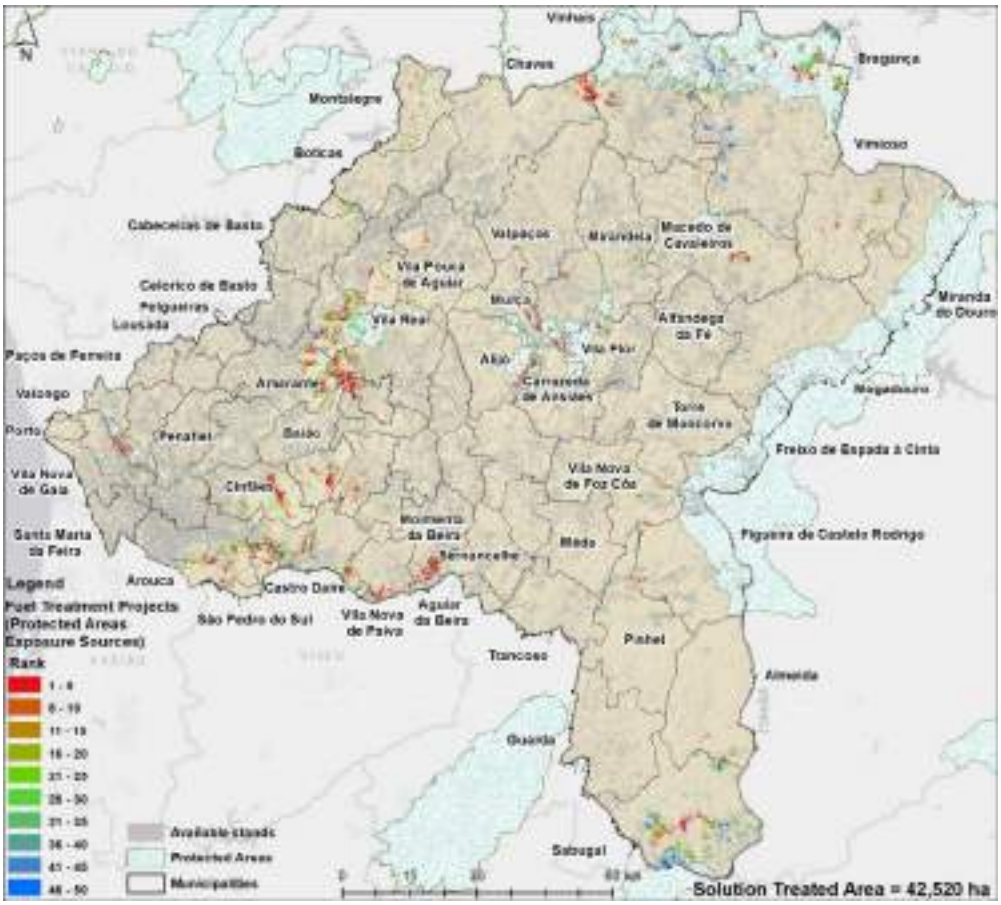

Figure 63 Map of the 50 best projects of each Municipality, ranked by the level of attainment they achieve, with the objective to reduce the exposure of protected areas from incoming wildfires (exposure sources).

Finally, in Figure 64 the Municipality of Montalegre achieved high attainment (~1.4%) by treating 1220 ha in 50 projects, followed by Mondim de Basto with ~1.2% with 2905 ha, and Cinfães and Sabugal with ~1.1% and 1740 and 4427 ha, respectively. All other Municipalities achieved attainments <0.8%. We also noticed a joint optimality in Cinfães with the objective of community exposure sources, and in Bragança with carbon.

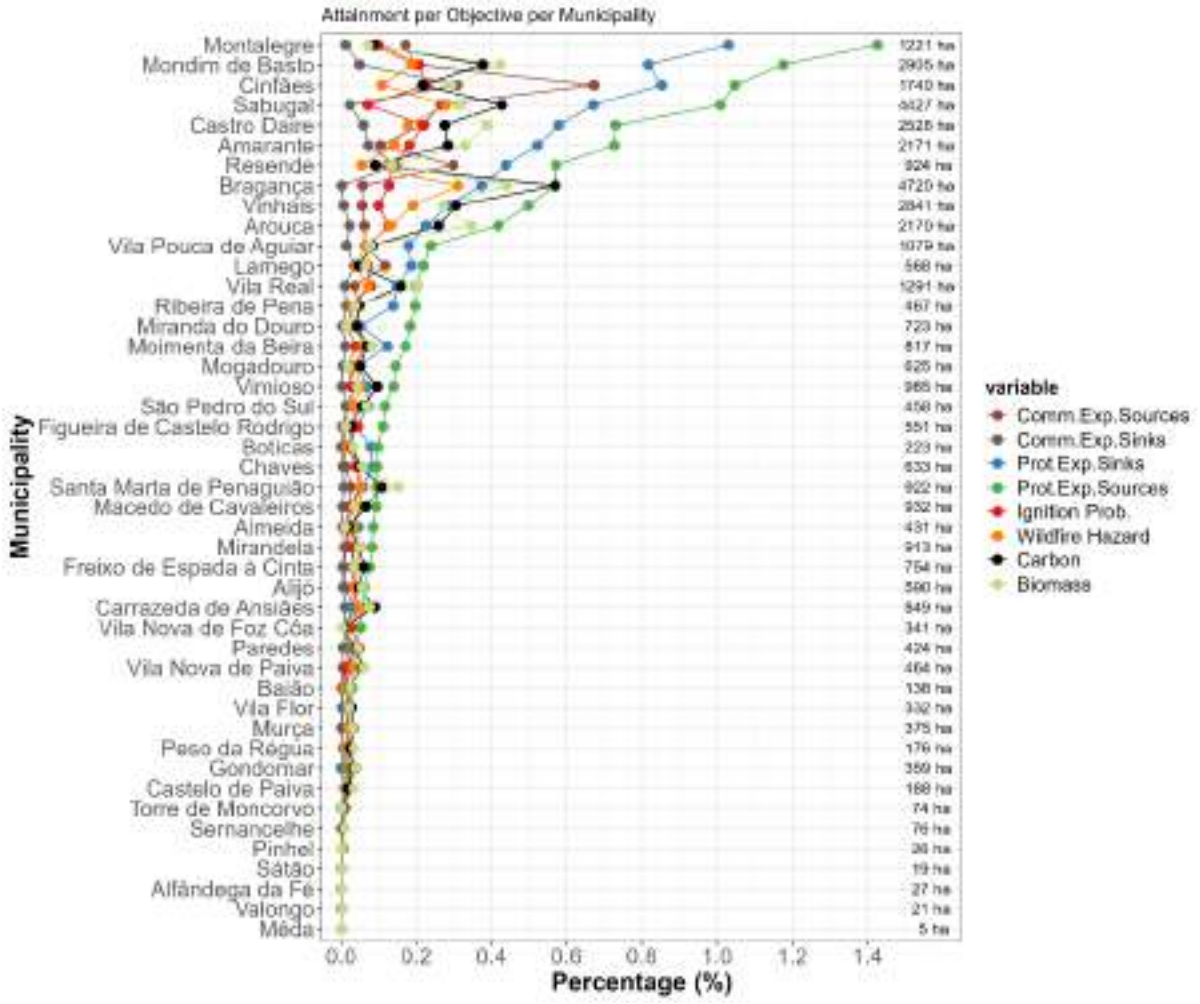

Figure 64 Attainment for each Municipality for the eight objectives when prioritized to reduce the exposure of protected areas from incoming wildfires (exposure sources).

The final run for this set prioritized fuel treatments for the management objective of limiting the ignition probability. In Figure 65 the attainment curve of the main objective (red line), although when starting and up to 25k ha is the best performing, as the treated areas increases and up to 60k ha is second in terms of attainment and behind the biomass, to end up achieving ~12% when all the solution area is treated (200k ha), ranked third and behind biomass (~21%) and carbon (~17%), and at the same final attainment with wildfire hazard. The objectives of community exposure sources achieved a ~10% attainment, while the protected areas (sources and sinks) a ~7%, and the community exposure sinks ~4%. In Figure 66 we can notice a good distribution of projects across the landscape, since all of the available stands had an ignition probability value greater than zero, so, there were plenty to select and build the projects.

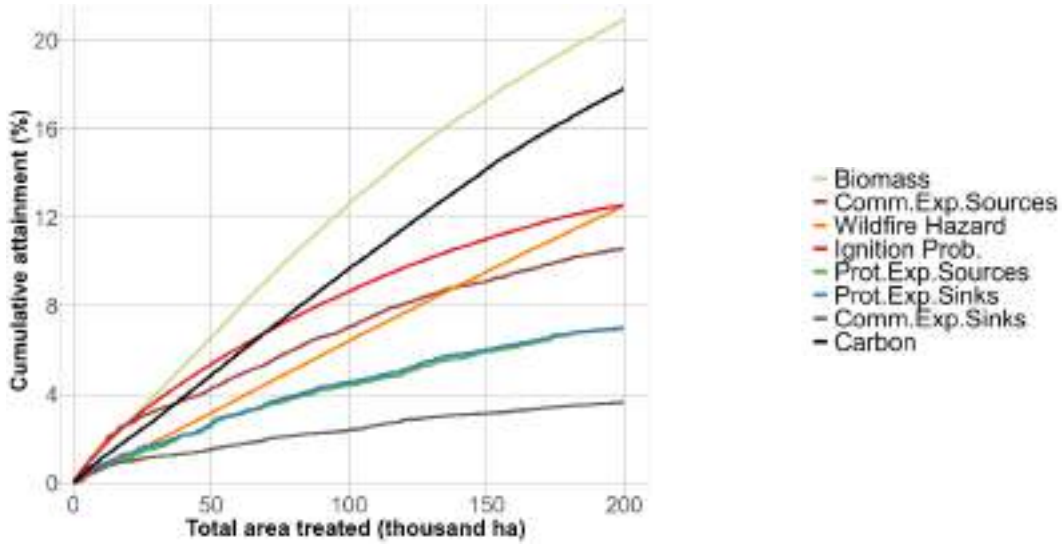

Figure 65 Area treated for all Municipalities and the level of attainment for all objectives after prioritizing for the objective to reduce new ignitions by treating in areas with high ignition probability.

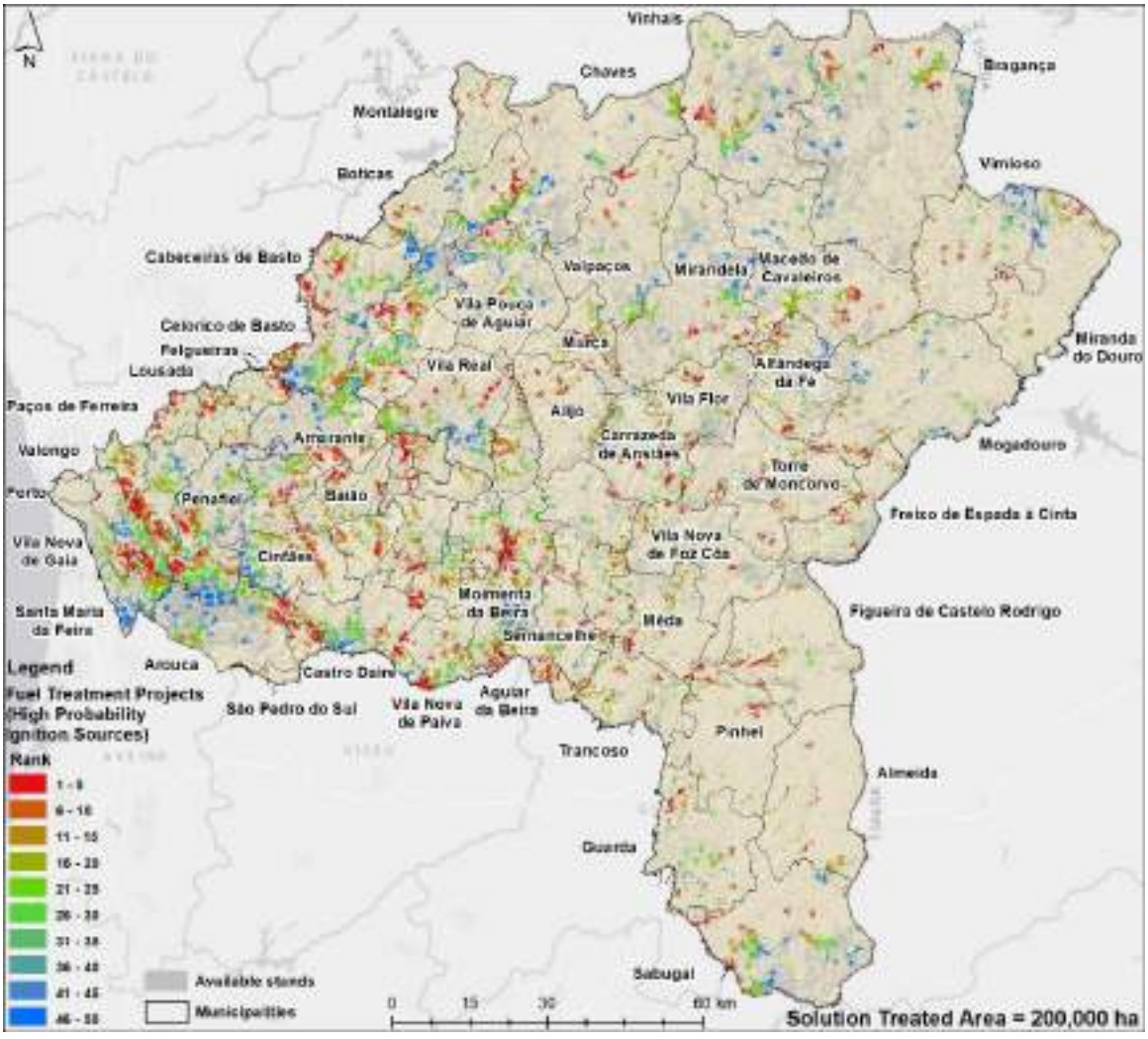

Figure 66 Map of the 50 best projects of each Municipality, ranked by the level of attainment they achieve, with the objective to reduce new ignitions by treating in areas with high ignition probability.

Finally, in Figure 67 the range of performance among the Municipalities is moderate to low, with the highest performing (Cabeceiras de Basto) achieving a ~0.75% and the lowest (Freixo de Espada à Cinta) a ~0.15% attainment. The treated area among the Municipalities ranged from 1500 to approximately 7000 ha. Some Municipalities, like Cinfães and Moimenta da Beira achieved high attainment for community exposure sources, while others like Mondim de Basto and Montalegre were high performing for protected areas exposure sources. Most Municipalities achieved high attainment for the objective of biomass and carbon, usually >0.4% and 0.2% respectively.

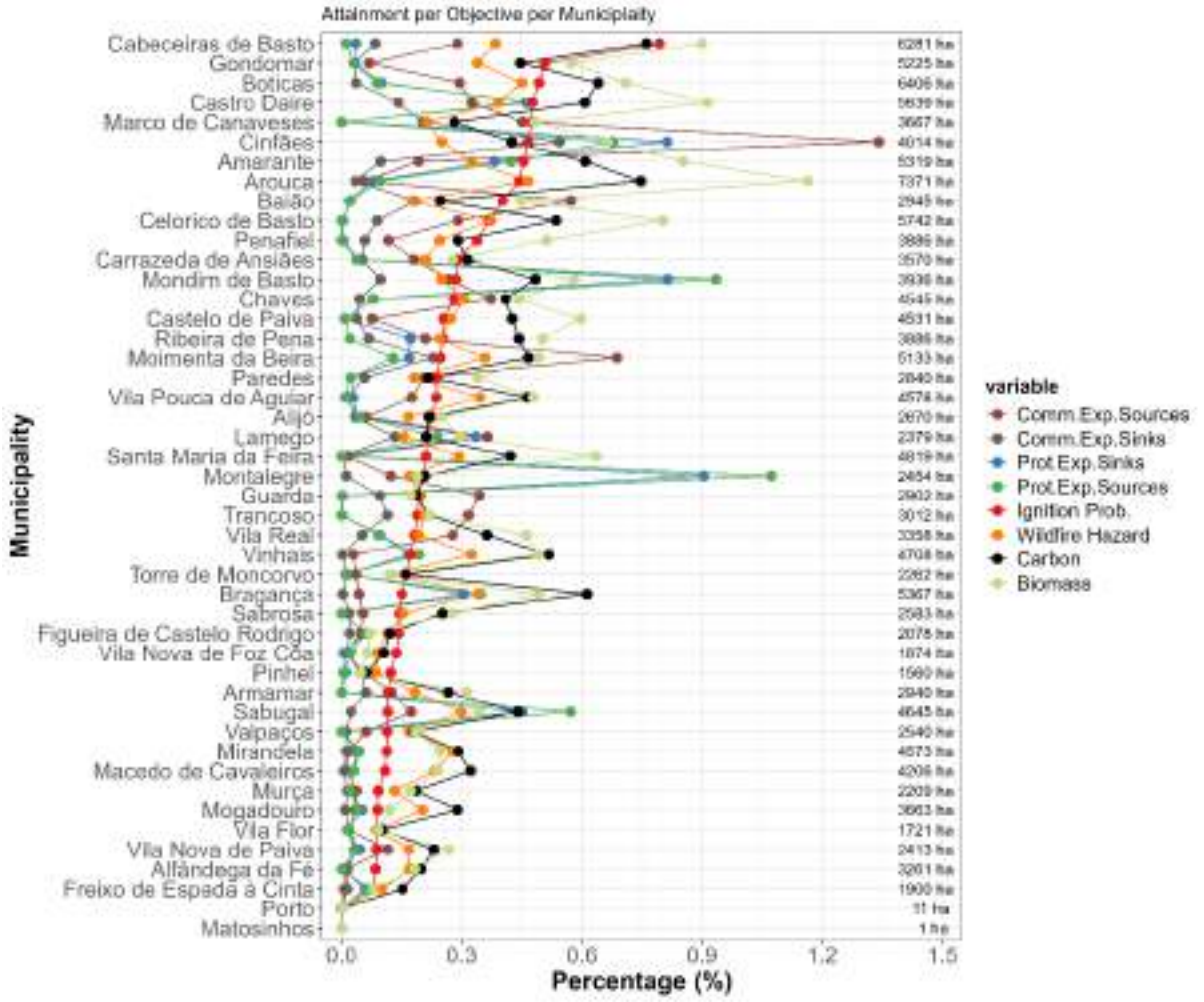

Figure 67 Attainment for each Municipality for the eight objectives when prioritized to reduce new ignitions by treated in areas with high ignition probability.

In Figure 68 we present all stands that met either more than two (orange) and three (red) objectives. There are about 100k ha of stands that meet at least two of the three main objectives examined above (community exposure sources, protected areas exposure sources and ignition probability), and 20k ha of stands that meet all three objectives (Figure 69). When we start selecting these stands based on the best available stands for the objective of community exposure sources, we notice that by treating approximately 30k ha we can achieve a ~8% for that objective, ~5% for the protected areas exposure sources, and 2% for the ignition probability (Figure 69-left). By selecting with the same

way, the stands that meet all three criteria, an attainment of community exposure sources of ~1.5% is achieved if we treat 10k ha, achieving a ~4% attainment for the protected areas sources and <1% for the other objectives. This is also a typical and realistic scenario of how much area can be potentially get treated each year. Even though it seems a low percentage, if these stands are identified and receive treatments then a large measurable difference can be made in only one year for the objectives of community exposure sources and protected areas sources.

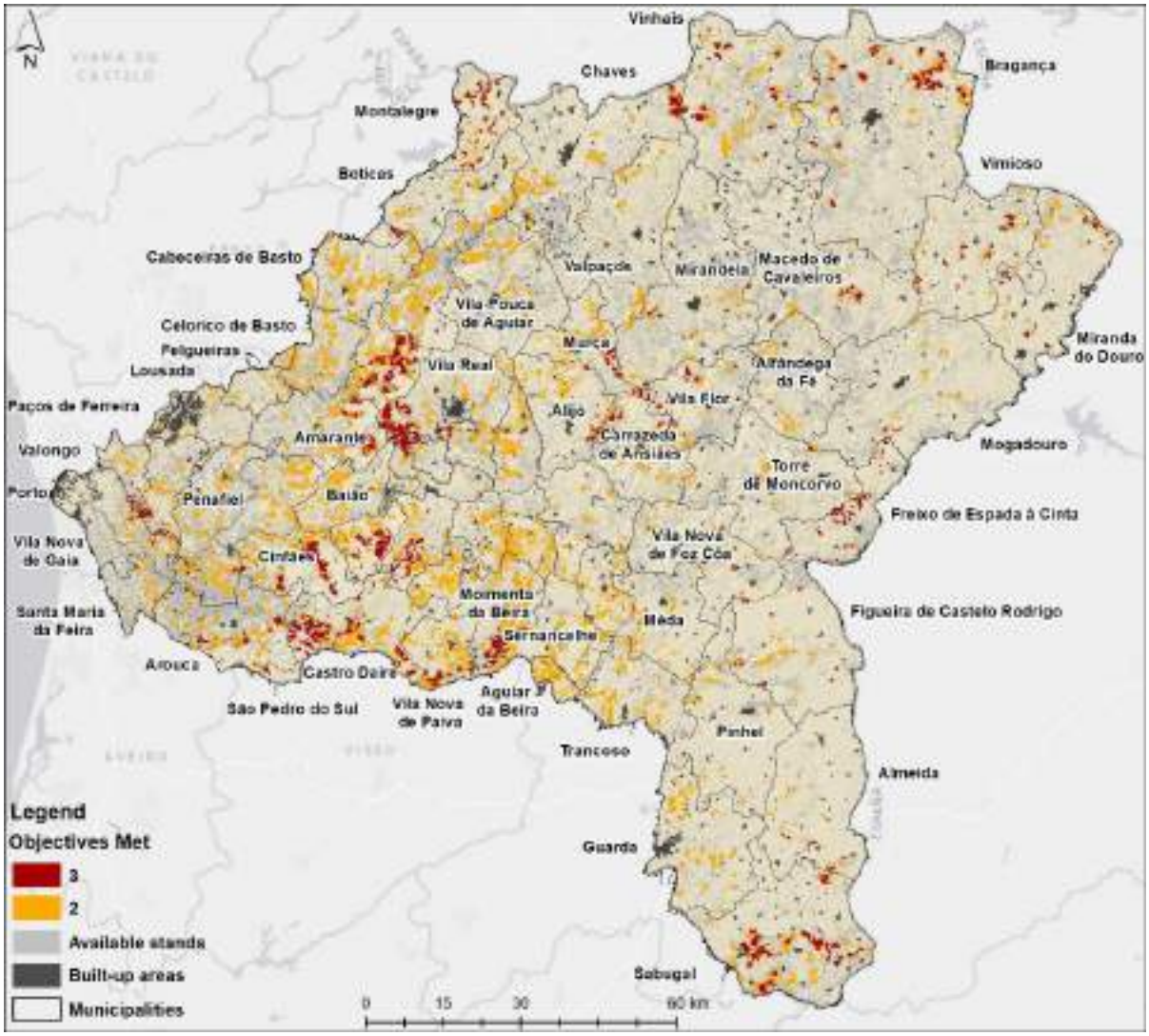

Figure 68 Allocation of stands that were selected from the three runs of SET2 that meet two or more objectives (orange) and three objectives (red).

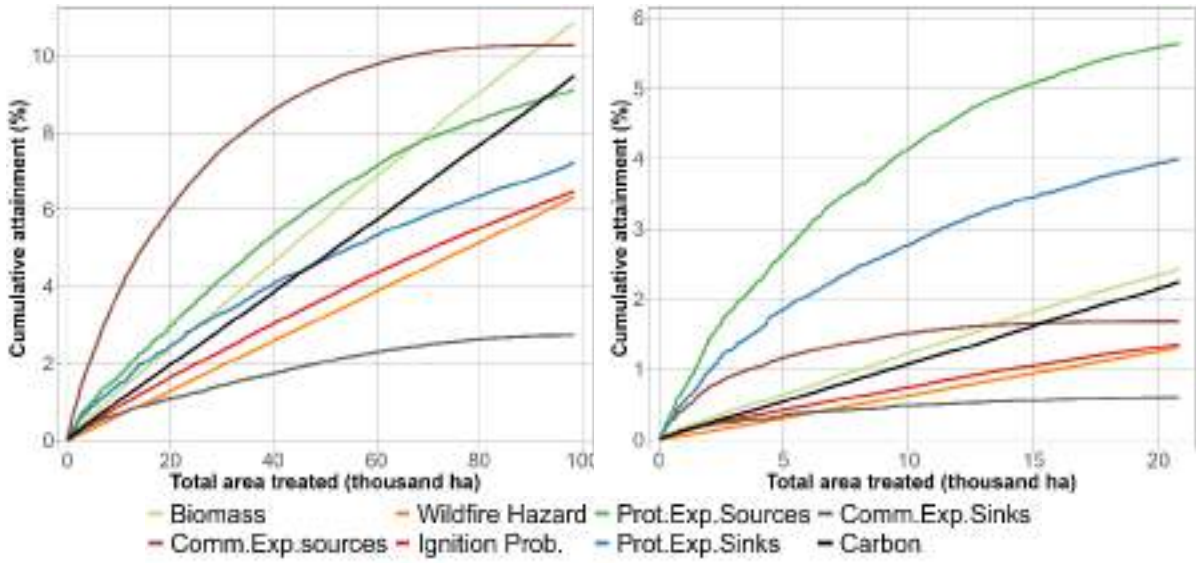

Figure 69 The attainment of the eight objectives analysed for the stands that were selected from the three runs of SET2 that a) meet two or more objectives (left) and b) meet three objectives (right). For graphing purposes, the stands selected first had the highest performance for the objective of community exposure sources.

4.2.4 SET3: Trade-offs and joint optimality

This set of runs revealed the potential existence of trade-offs between different couples of management objectives and mapped the joint optimality on the spatial allocation of projects across each managing landscape. We note here that a couple of objectives do not necessarily mean the existence of trade-offs. These trade-offs were examined at the scale of Municipalities. In addition, although some Municipalities might show strong trade-offs, others might have none. The first couple examined the community exposure sources vs. the protected area sources. The map in Figure 66 shows a solution of approximately 32,000 ha for the three examined weight combinations (equal, 10-3 and 3-10) and creates a maximum difference of 0.4% in the attainment of protected areas exposure sources, while the attainment for the community exposure sources remains unchanged. Blue- and orange-coloured projects that overlap with the equal weighing scheme are not visible, and they only appear where these projects were not selected by the other two weighting schemes. The overall attainment for the management objective of community exposure sources is 2.7%, while for the protected areas approximately 9.5%. Most of the projects spatially coincide and only few differentiate at the Municipalities of Sabugal, Mondim de Basto and Amarante for the weight combination 10-3 (orange colour), and few in Sabugal, Vila Real and Arouca for the weight combination 3-10 (blue colour).

The trade-off graph in Figure 71 shows either minor and insignificant changes in the attainment between the two objectives on the different Municipalities (e.g., Castro Daire and Amarante), or had a joint optimality, i.e., the increase in attainment on one objective had an increase also in the other (e.g., Cinfães) or were stable like the cases of Montalegre and Bragança where the attainment of community exposure remained approximately at the same levels while the attainment of the protected areas was increasing.

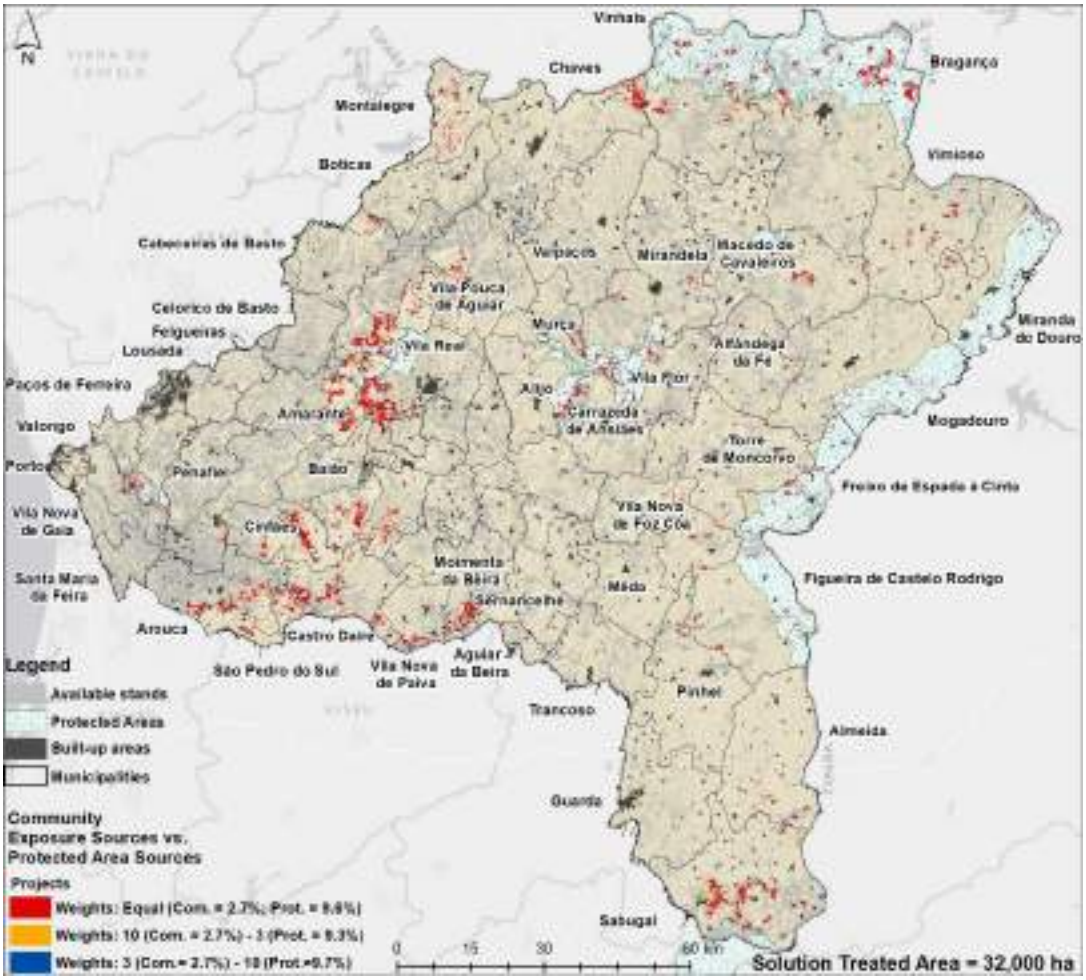

Figure 70 Trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Developed areas exposure sources objective weight maximized (10) and protected areas exposure sources set to low (3) (orange); c) Protected areas exposure sources objective weight maximized (10) and developed areas exposure sources set to low (3) (blue). Blue- and orange-coloured projects that overlap with the equal weighing scheme are not visible, and they only appear where these projects were not selected by the other two weighting schemes.

In Figure 72 we show the performance of each objective on each of the 30 Municipalities with the most projects allocated on them, for five different weight combinations. If the red or black dots portray large fluctuations in their attainment this means that they are influenced when the weighting scheme is changed, while if they remain at the same levels of attainment, it means that same treated area has the same footprint on this objective no matter how they are arranged on the landscape. In all cases, the protected areas achieved higher attainment (red dots at the right). Notable fluctuations in the attainment were recorded for the Municipalities of Amarante, Montalegre and Cinfães. These results revealed that we should not expect any strong trade-offs or joint opportunities when we compare these two objectives on their attainment across the different Municipalities.

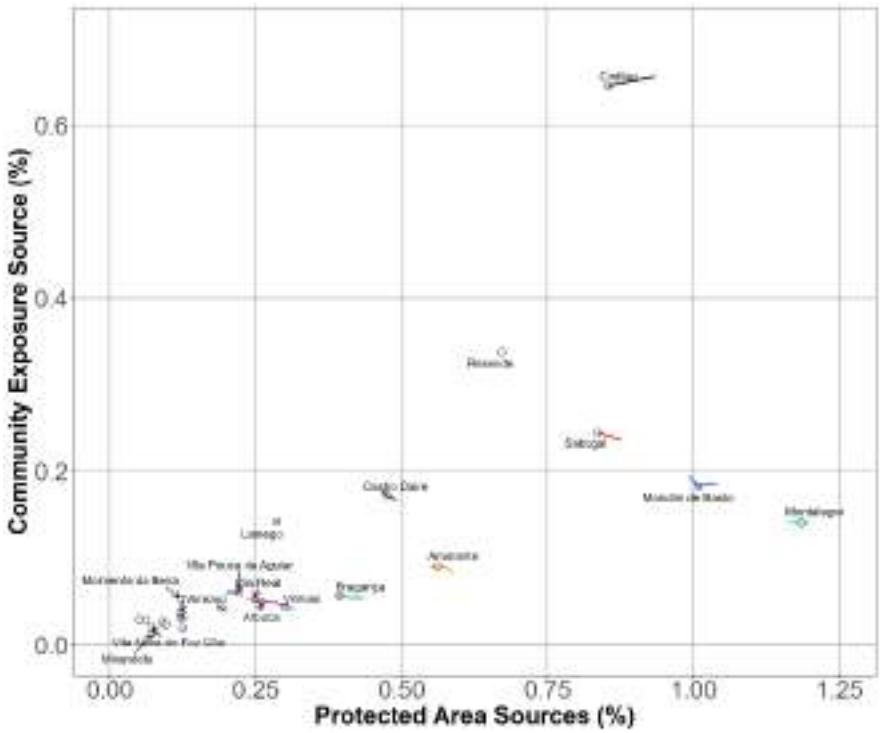

Figure 71 Trade-off production probability curves for each Municipality for the objectives of developed areas exposure sources vs. the protected areas sources. Axes show the level of attainment for each objective (%).

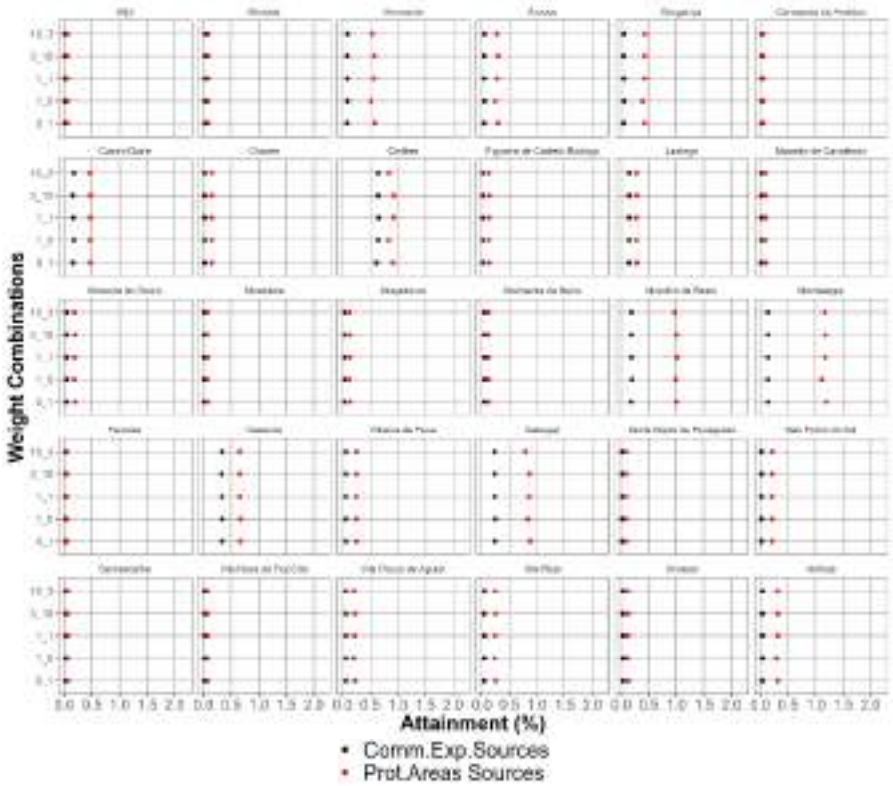

Figure 72 Each panel shows the attainment of each of the two objectives (black: developed areas exposure sources; red: protected areas exposure sources) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Municipality.

The second couple examined was the community exposure sources vs. biomass. The map in Figure 73 shows a solution of approximately 90,000 ha for the three examined weight combinations and creates a substantial maximum difference of 1.7% in the attainment of the community exposure sources, and 0.7% for biomass. The overall attainment for the management objective of community exposure sources is approximately 11%, while for the biomass approximately 10%. While several of the proposed projects spatially coincide, there are several that differentiate at the Municipalities of Vila Real, Vila Pouca de Aguiar, Vinhais, Sabugal and Mondim de Basto for the weight combination 10-3 (orange colour), and several in Arouca, Cabeceiras de Basto, Sabugal and Vila Pouca de Aguiar for the weight combination 3-10 (blue colour).

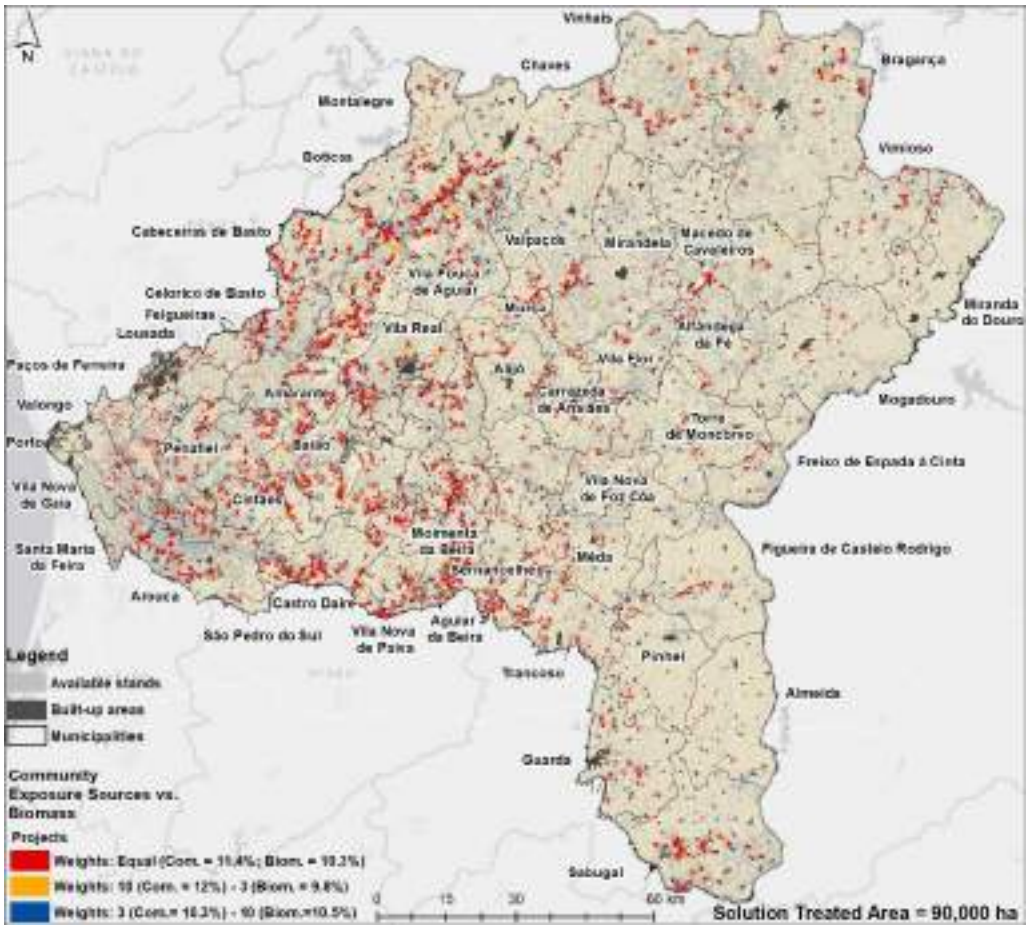

Figure 73 Trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Developed areas exposure sources objective weight maximized (10) and retrieved biomass set to low (3) (orange); c) retrieved biomass objective weight maximized (10) and developed areas exposure sources set to low (3) (blue). Blue- and orange-coloured projects that overlap with the equal weighing scheme are not visible, and they only appear where these projects were not selected by the other two weighting schemes.

The trade-off graph in Figure 74 shows sharp differences for most of the Municipalities, especially for Ribeira de Pena, Vila Real, Baião and Sabugal (i.e., the more the attainment of the community exposure sources is increased, the more the biomass is decreased). These curves suggest that there are opportunities for a spatial allocation of projects (i.e., projects from a weight combination at the middle of each curve) that can achieve

relatively high attainments for both management objectives. Overall, the attainment capacity of this objective combination is moderate, since the highest performing Municipality like the Cinfães can achieve a maximum of 1.25% attainment for the community exposure sources with approximately 0.4% for biomass, while the highest performing curve for biomass is in the Municipality of Castro Daire, with approximately 0.45% attainment (and 0.2% for community exposure). There are several other Municipalities with sharp trade-offs, like Montalegre, Paredes, Trancoso and Tarouca, but their overall attainment for both objectives is relatively low.

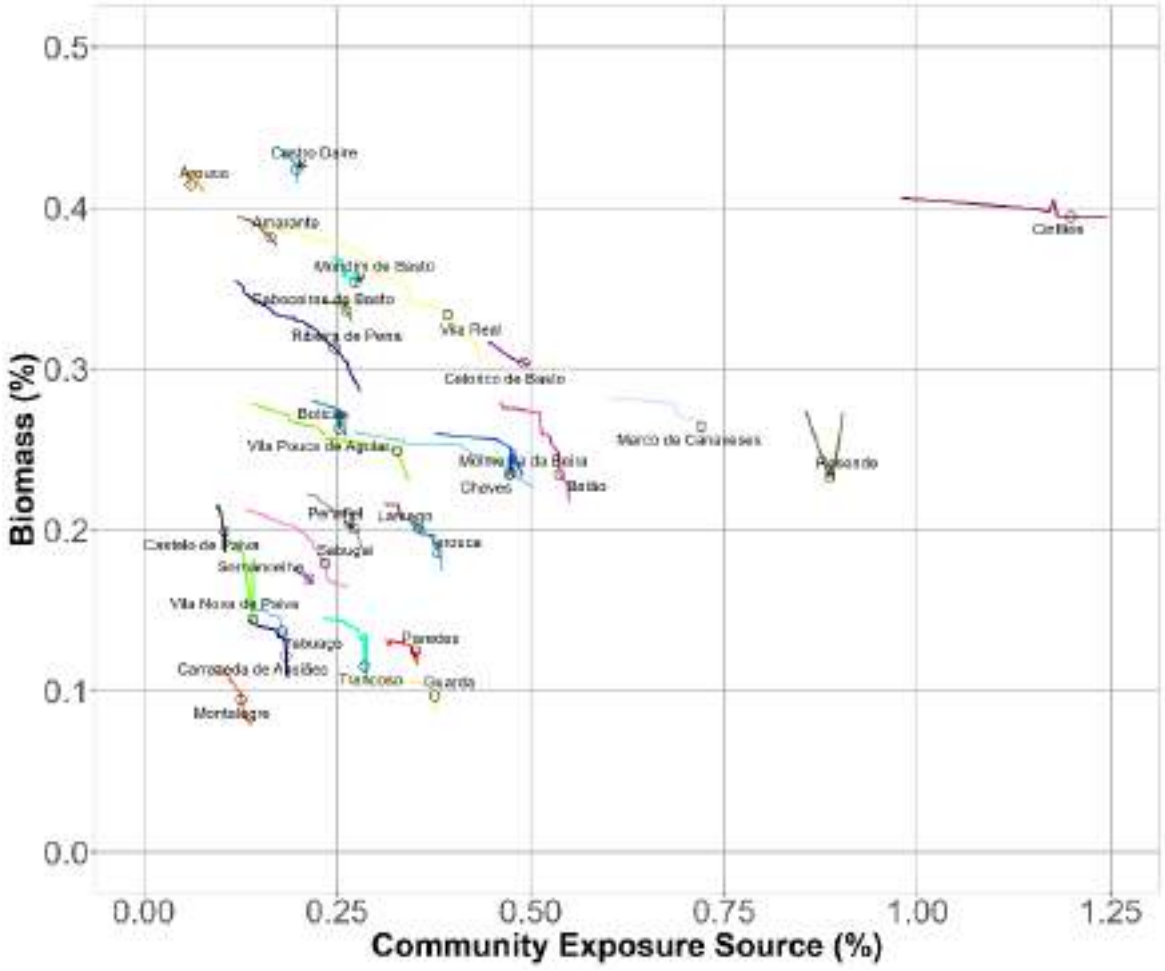

Figure 74 Trade-off production probability curves for each Municipality for the objectives of retrieved biomass vs. developed areas exposure sources. Axes show the level of attainment for each objective (%).

In Figure 75 we noticed large fluctuations in the attainment of the Municipalities of Cinfães, Chaves, Marco de Canaveses, Vila Real and Vila Pouca de Aguiar for the community exposure objective. The biomass objective has much smaller fluctuations for some Municipalities, like Vila Real, Ribeira de Pena and Baião. In most cases, the community exposure sources achieved higher attainment (black dots at the right), but there are some cases like the Municipalities of Ribeira de Pena, Castro Daire and Arouca where biomass has a better performance (red dots at the right). Compared to the previous couple of objectives, this one has evident trade-offs when the weighting scheme

is changed, an evident fact from the appearance of different colours on the map (orange and blue instead of just red), the curved shape of the Municipality lines, and the large fluctuations in the dots of the attainment graph.

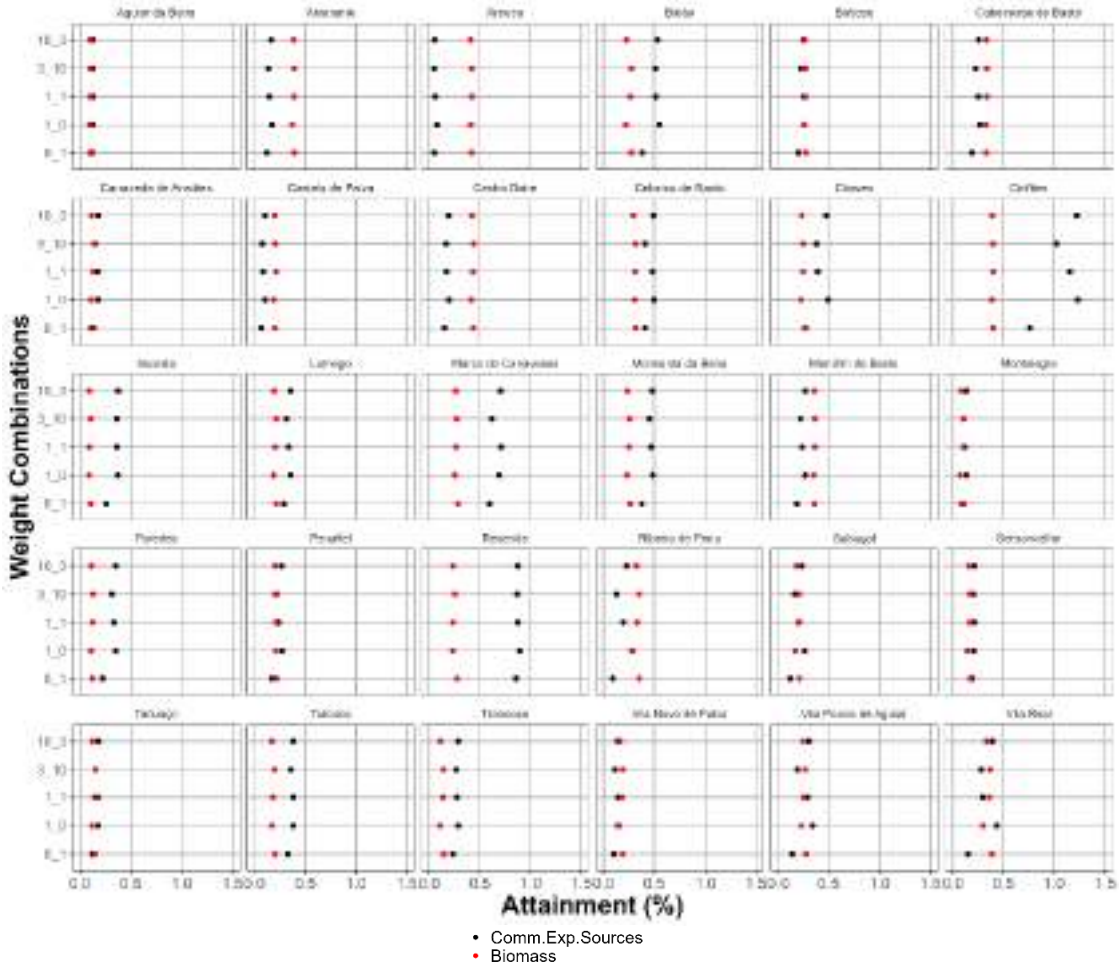

Figure 75 Each panel shows the attainment of each of the two objectives (black: developed areas exposure sources; red: biomass retrieved) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Municipality.

The third couple examined the community exposure sources vs. sinks. The map in Figure 76 shows a solution of approximately 35,000 ha for the three examined weight combinations and creates a small maximum difference of 0.3% in the attainment of the community exposure sources, and 0.5% for the sinks. The overall attainment for the management objective of community exposure sources is approximately 6.4%, while for the sinks approximately 5%. While several of the proposed projects spatially coincide, there are some that differentiate at the Municipalities of Amarante, Vila Real, Cinfães and Castro Daire for the weight combination 10-3 (orange colour), and several in Amarante, Cabeceiras de Basto, Sabugal and Ribeira de Pena for the weight combination 3-10 (blue colour).

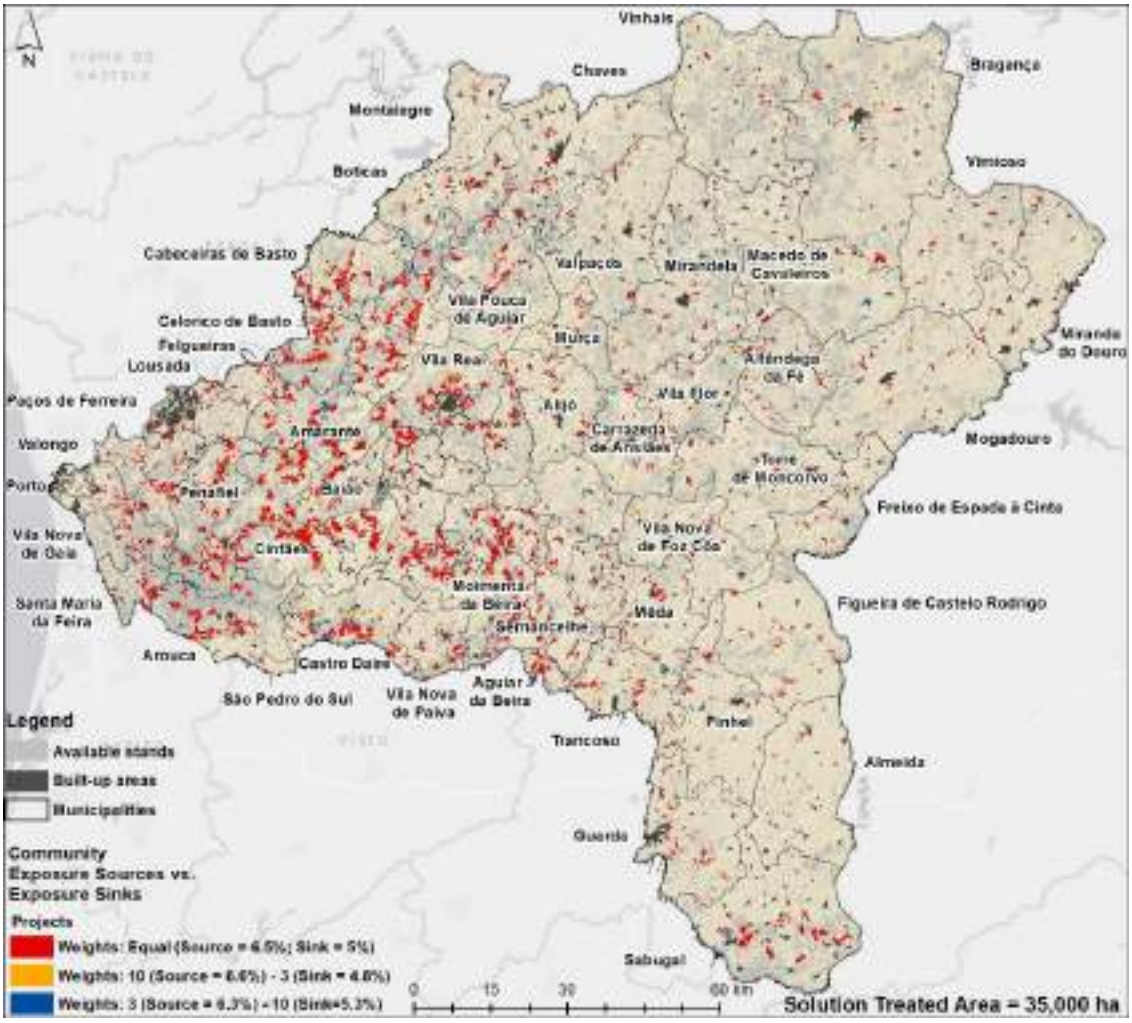

Figure 76 Trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Developed areas exposure sources objective weight maximized (10) and developed areas exposure sinks set to low (3) (orange); c) Developed areas exposure sinks objective weight maximized (10) and developed areas exposure sources set to low (3) (blue). Blue- and orange-coloured projects that overlap with the equal weighing scheme are not visible, and they only appear where these projects were not selected by the other two weighting schemes.

The trade-off graph in Figure 77 shows sharp differences for most of the Municipalities, especially for Moimenta da Beira, Marco de Canaveses, Sabugal, Chaves and Baião (i.e., the more the attainment of the community sinks is increased, the more the sources is decreased). Overall, the attainment capacity of this objective combination is low, since the highest performing Municipality like the Marco de Canaveses can achieve a maximum of 0.55% attainment for the community exposure sources with approximately 0.35% for sinks, while the highest performing curve for community sinks is in the Municipalities of Marco de Canaveses and Resende, with approximately 0.35% attainment (and ~0.5% for community exposure sources).

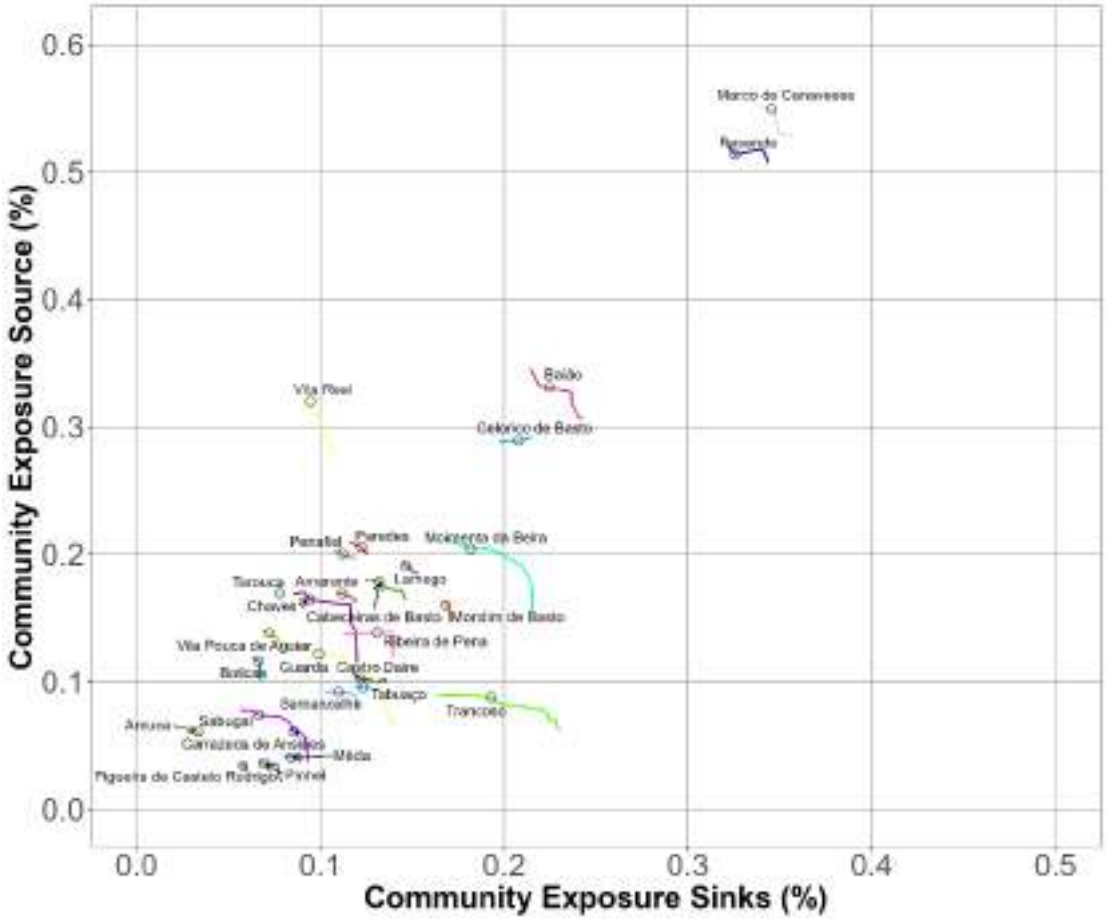

Figure 77 Trade-off production probability curves for each Municipality for the objectives of developed areas exposure sources vs. developed areas exposure sinks. Axes show the level of attainment for each objective (%).

In Figure 78 we noticed large fluctuations in the attainment of a few Municipalities, with most notable those of Vila Real, Moimenta da Beira, Trancoso, Guarda and Resende. These fluctuations cause in some weight combinations to alternate which objective achieves higher attainment. We also notice fluctuations in the attainment of each objective individually, for example, in Chaves the combination of 10-3 cause the sources to achieve 0.18% attainment and sinks 0.09%, while the combination 0-1 cause the sources and sinks to achieve the same attainment (0.1%). Some Municipalities, like Arouca, Gondomar, Tabuaço and Mondim de Basto have a stable pattern of attainment for both the objectives across all weight combinations. Last, community exposure sinks achieved better attainment for the Municipalities of Trancoso, Mêda and Pinhel, meaning that there is more efficient to protect communities close or inside their boundaries compared to the rest of Municipalities, where it is more preferable to choose projects from weight combinations that achieved with high attainment for the sources and focus on mitigating fire risk in the locations where large fires initiate and spread into the communities. Here again, this couple has evident trade-offs, but only for some Municipalities, when the weighting scheme is changed, an evident fact from the appearance of different colours on the map (orange and blue instead of just red), the

curved shape of the Municipality lines, and the moderate fluctuations in the dots of the attainment graph.

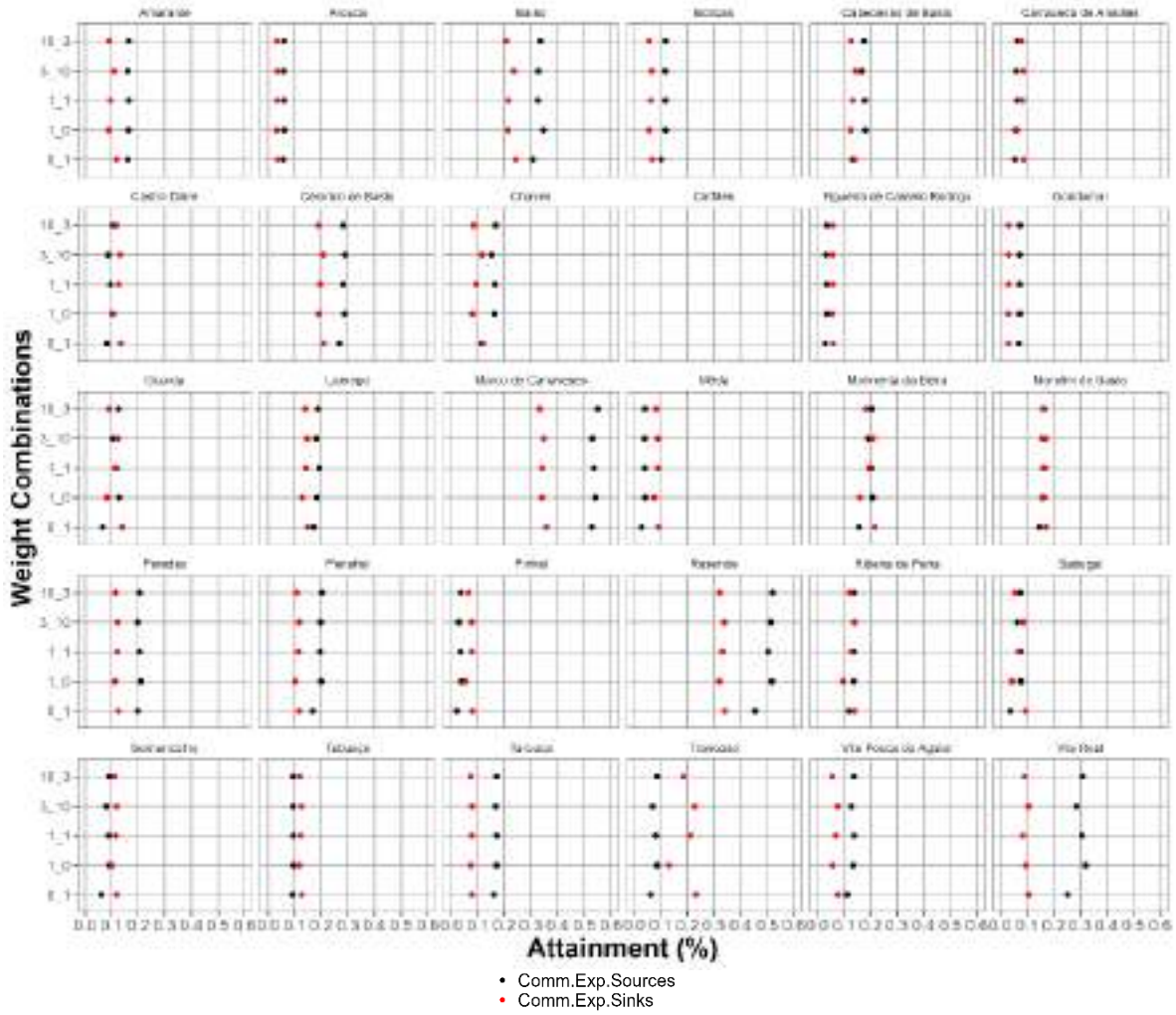

Figure 78 Each panel shows the attainment of each of the two objectives (black: developed areas exposure sources; red: developed areas exposure sinks) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Municipality.

The last couple of objectives examines whether it is better to apply fuel treatments on projects inside the protected areas (sinks) or where the fire risk originates (either inside or outside protected areas – sources). The map in Figure 79 shows a solution of approximately 28,500 ha for the three examined weight combinations and creates a minor maximum difference of 0.2% in the attainment of the protected areas exposure sources, and 0.2% for the sinks. The overall attainment for the management objective of protected areas exposure sources is approximately 8.5%, while for the sinks approximately 7%. Most projects spatially coincide, except for some projects inside the Municipalities of Amarante, Sabugal, Bragança and Castro Daire, among others. In Figure 80 we notice only some minor fluctuations in the performance of the Municipalities of Montalegre, Resende and Castro Daire, but without a clear trade-off curve or pattern. Almost all other Municipalities either have non-evident trade-off curves with very low attainment or have minor and unimportant changes.

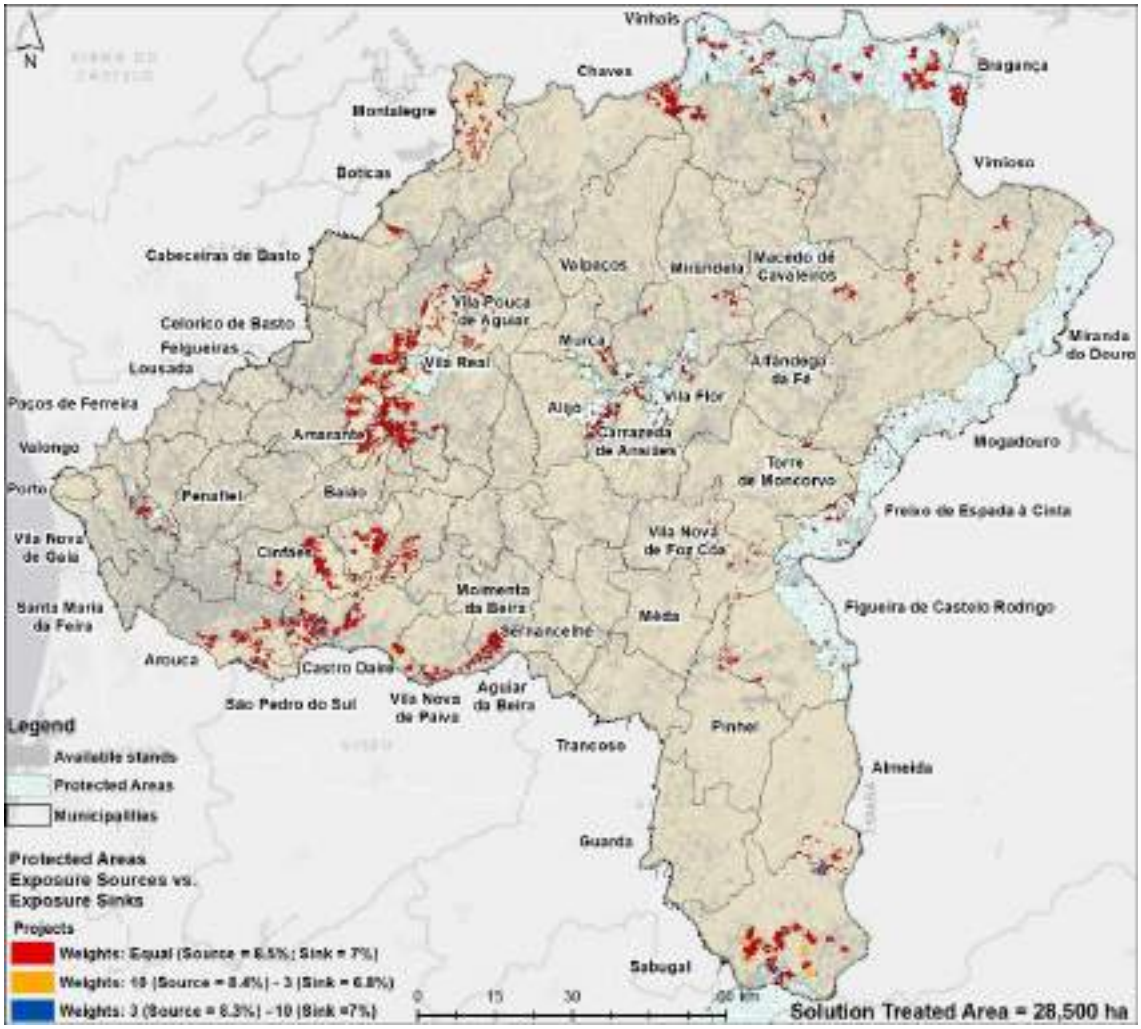

Figure 79 Trade-off scenario planning runs with three weighting schemes: a) equal weights (red); b) Protected areas exposure sources objective weight maximized (10) and protected areas exposure sinks set to low (3) (orange); c) Protected areas exposure sinks objective weight maximized (10) and protected areas exposure sources set to low (3) (blue). Blue- and orange-coloured projects that overlap with the equal weighing scheme are not visible, and they only appear where these projects were not selected by the other two weighting schemes.

Finally, in Figure 81 we noticed stable patterns of attainment for each objective and for each Municipality. Small fluctuations were found in the attainment of the Municipalities of Montalegre, Sabugal and Mondim de Basto for the objective of protected areas exposure sources, while the Municipalities of Montalegre, Resende and Sabugal had small attainment changes for the objective of protected areas exposure sinks. This couple of objectives has no evident trade-offs when the weighting scheme is changed, i.e., no appearance of different colours on the map except for red, no curved shaped Municipality lines, and minor fluctuations in the dots of the attainment graph.

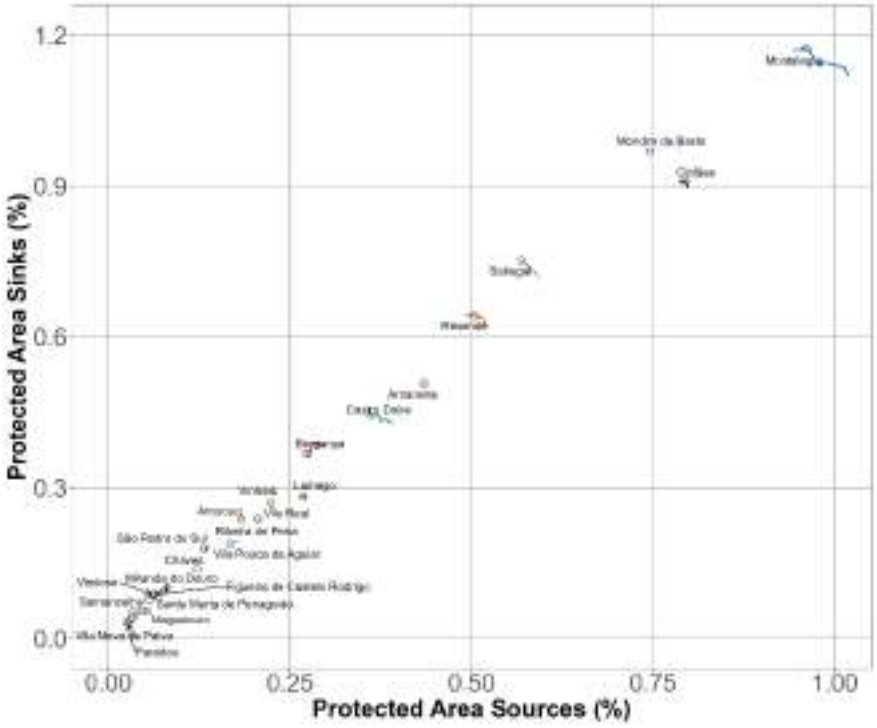

Figure 80 Trade-off production probability curves for each Municipality for the objectives of protected areas exposure sources vs. protected areas exposure sinks. Axes show the level of attainment for each objective (%).

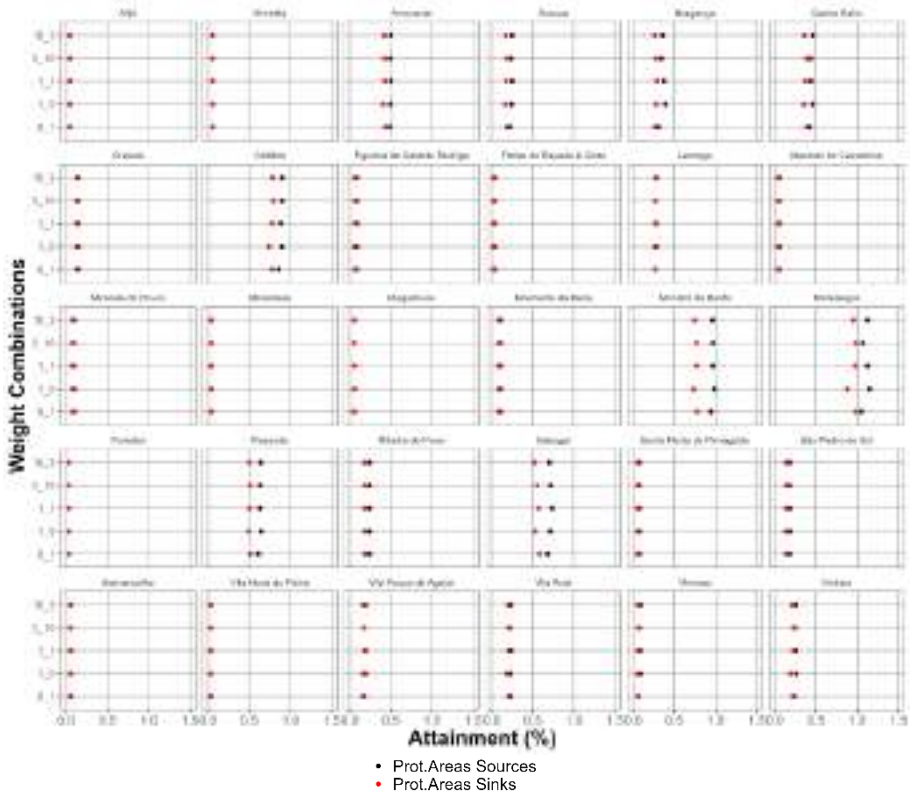

Figure 81 Each panel shows the attainment of each of the two objectives (black: protected areas exposure sources; red: protected areas exposure sinks) of five weighting combinations (10-3; 3-10; 1-1; 1-0; 0-1) for each Municipality.