

Results

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This document detail all the method used to obtain the results of the study. All results presented here are not on the report.

I. set up

Working directory and used pakages:

```
wd = "D:/Internship 3A/GitHub/Project-Klamath-2021/Outputs/R"

setwd(wd)
library(magrittr)
library(cowplot)
library(ggplot2)
library(raster)
library(knitr)
library(tibble)
library(dplyr)
```

Input folders and name of the scenarios:

```
BAU_input =
  "E:/FIF/Stage 3A/Extract/Documents/Klamath_(CA_only)_2021 - Harvest BAU/"
Adapty_input =
  "E:/FIF/Stage 3A/Extract/Documents/Klamath_(CA_only)_2021 - Harvest Adaptability/"
ProAct_input =
  "E:/FIF/Stage 3A/Extract/Documents/Klamath_(CA_only)_2021 - Harvest Pro-active/"

ListScenario = c("Business as usual", "Adaptability", "Pro-Active")
```

Palettes of color used for map plot:

```
pal.3 = colorRampPalette(c("grey", "purple", "yellow"))

pal.sd = colorRampPalette(c("grey", "blue", "cyan"))

pal.dif = colorRampPalette(c("red", "tomato", "darkgoldenrod1", "cyan3", "cyan", "blue"))
```

Some of the rasters used in this part have not a defined system of projection. The one of the management area is used as a reference for rasters that will be exported.

```

Ownership_OnlyCA = raster("D:/Internship 3A/GitHub/Project-Klamath-2021/Model Parameterization/R inputs
CRSRef = crs(Ownership_OnlyCA)
NrowRef = Ownership_OnlyCA@nrows
NcolRef = Ownership_OnlyCA@ncols
ResRef = res(Ownership_OnlyCA)[1]
XminRef = Ownership_OnlyCA@extent@xmin
XmaxRef = Ownership_OnlyCA@extent@xmax
YminRef = Ownership_OnlyCA@extent@ymin
YmaxRef = Ownership_OnlyCA@extent@ymax

```

II. Carbon balance

If the management scenarios were improving adaptation, the mitigation of climate change by stocking carbon is an important ecosystem service that is usually used for international environmental policy purposes. The NEEC (Net Ecosystem Exchange of Carbon) measures the total flux of carbon (difference between carbon fixed on the ecosystem and carbon released on the atmosphere).

The general method used to obtain the data is common for all the results. For all the two model run (stocked in files names “.1” and “.2”, cf. Inputs) and for all scenarios, the output file (here the *NECN-succession-log.csv* table) is imported. The interest data (here NEEC column) is selected, aggregated (no need to differentiate the ecoregions) and characterised by run and scenario. The 6 data frame created (2 runs for the 3 scenarios) are then merged into a final one *NEEC*.

```

NEEC = data.frame()

for(j in c(1,2)){

  if(j == 1) { run = "..1"
  } else { run = "..2"}

  for(scenario in ListScenario){

    if(scenario == "Business as usual") {Input = BAU_input
    } else if(scenario == "Adaptability"){Input = Adapty_input
    } else {Input = ProAct_input}

    NECNlog = paste0(Input, run, "/NECN-succession-log.csv") %>% read.csv()
    NEEClog = aggregate(NECNlog$NEEC, by=list(Time=NECNlog$Time), FUN=sum)
    colnames(NEEClog) = c("Time", "NEEC")
    NEEClog$NEEC = NEEClog$NEEC*10^-6 # conversion g/m² to Mg/m²
    NEEClog$Scenario = scenario
    NEEClog$Run = j

    NEEC = rbind(NEEC, NEEClog)
  }
}

```

The obtained dataframe gives the NEEC for each year, scenario and run of the model.

```
kable(as.data.frame(head(NEEC)),
      caption = "Insight of the data used concerning the Net Ecosystem Exchange of Carbon")
```

Table 1: Insight of the data used concerning the Net Ecosystem Exchange of Carbon

Time	NEEC	Scenario	Run
0	0.0000000	Business as usual	1
1	-0.0493470	Business as usual	1
2	-0.0575344	Business as usual	1
3	-0.0524389	Business as usual	1
4	-0.0521461	Business as usual	1
5	-0.0541290	Business as usual	1

To compare the NEEC between scenarios and disturbances, it is first added for a same scenario and on for same run (*Mortality_Sum*). After that, a mean of the NEEC calculated is obtained, using the results of the two runs. Thus, a mean of total mortality is obtained for a same scenario (*Mortality_Agg*).

In addition, the standard deviation between the runs is calculated to measure the variability of the model. As the function *sd()* is used for the “sample standard deviation” *s* (equation 1), it uses the Bessel’s correction. As here the data is not a sample of an existing population but results of models, we multiply the standard deviation calculated by the inverse of the Bessel factor to obtain the uncorrected standard deviation *s_n* (equation 2).

Equation 1:

$$s = \sqrt{\frac{\nu}{1 - n}}$$

Equation 2:

$$s_n = \sqrt{\frac{\nu}{n}}$$

$$\Leftrightarrow s_n = s \sqrt{\frac{n - 1}{n}}$$

With:

- *n* the number of observations on a sample. As we are considering results of runs and the variability between them, the number of observations is here the number of runs.
- ν the sum of squares deviation from the mean.

The coefficient $\sqrt{\frac{n - 1}{n}}$ is stocked in the variable called *InvBessel* and will be used for all standard deviation calculus on this work.

```
NEEC_Sum = NEEC %>% group_by(Scenario, Run) %>%
  summarise(NEECSum = sum(NEEC))

InvBessel = (ncol(NEEC)-1)/ncol(NEEC_Sum) %>% sqrt()

NEEC_Agg = NEEC_Sum %>% group_by(Scenario) %>%
  summarise(NEECMean = mean(NEECSum), NEECSd = sd(NEECSum)*InvBessel)
```

Finally, to plot the data against time, the mean and standard deviation are calculated for each year. The operations are done in the same way than above.

```
NEEC_AggT = NEEC %>% group_by(Time, Scenario) %>%
  summarise(NEECMean = mean(NEEC), NEECSd = sd(NEEC)*InvBessel)
```

The NEEC is plotted for each scenario.

```
ggplot(NEEC_AggT, aes(x=Time, y=NEECMean, col=Scenario, group=Scenario)) +
  geom_line(size = 1)+
  geom_errorbar(aes(ymin=NEECMean-NEECSd, ymax=NEECMean+NEECSd)) +
  xlab("Time (years)") +
  ylab("NEEC(Mg.m-2.yr-1)") +
  ggtitle("Evolution of Net Ecosystem Exchange of Carbon") +
  theme(plot.title = element_text(hjust = 0.5))
```

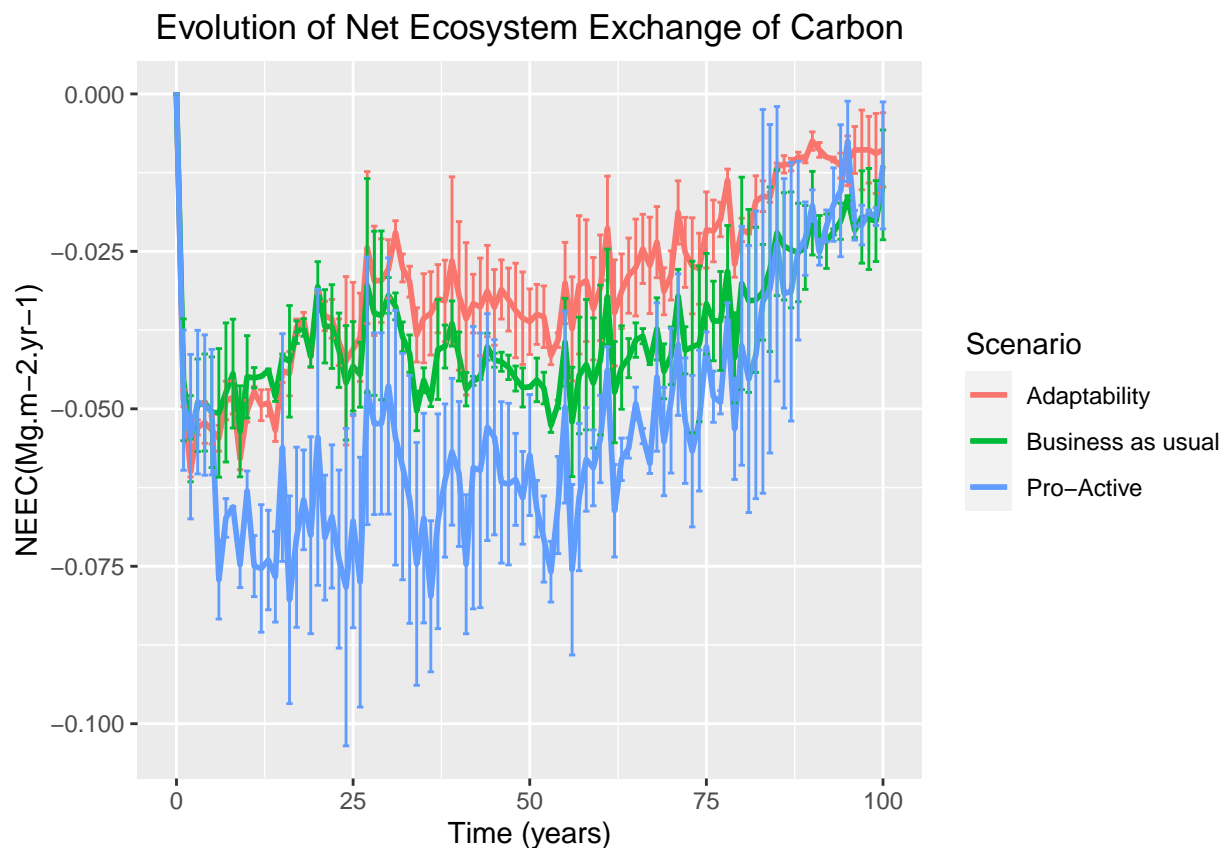


Figure 1: Evolution of Net Ecosystem Exchange of Carbon

It doesn't seem to give interesting information concerning the question. Thus, the total NEEC by scenario is plotted, to compare the global fluxes of carbon of the ecosystem on the 100 years of run.

```
ggplot(NEEC_Agg, aes(x=Scenario, y=NEECMean, fill=Scenario)) +
  geom_bar(stat="identity") +
  geom_errorbar(aes(ymin=NEECMean-NEECSd, ymax=NEECMean+NEECSd)) +
```

```
ylab("NEEC (Mg.m-2)") +
ggtitle("Total Net Ecosystem Exchange of Carbon") +
theme(plot.title = element_text(hjust = 0.5))
```

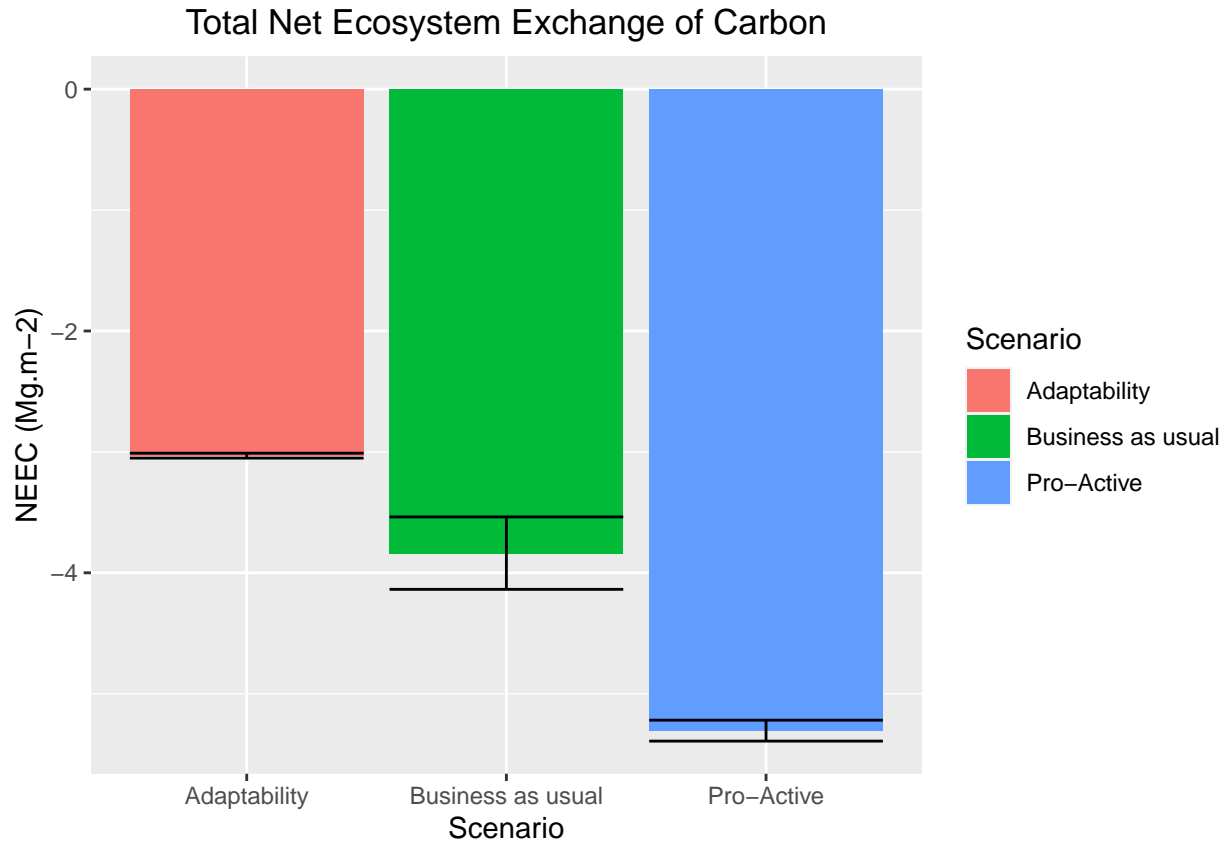


Figure 2: Total Net Ecosystem Exchange of Carbon

All the values are negative, signifying that the ecosystem, in all scenarios, stock more carbon than it releases in the atmosphere. The quantity of carbon stored increases with the degree of human intervention in the scenarios, showing the success of plantation strategie to stock carbon. Thus, with this criteria, the suitable management for climate adaptation is the Pro-active one.

For the defense,a more accesible graphic is created with the absolute values.

```
ggplot(NEEC_Agg, aes(x=Scenario, y=abs(NEECMean), fill=Scenario)) +
geom_bar(stat="identity") +
geom_errorbar(aes(ymin=abs(NEECMean)-NEECSD, ymax=abs(NEECMean)+NEECSD)) +
ylab("|NEEC| (Mg.m-2)") +
ggtitle("Total Carbon stocked") +
theme(plot.title = element_text(hjust = 0.5))
```

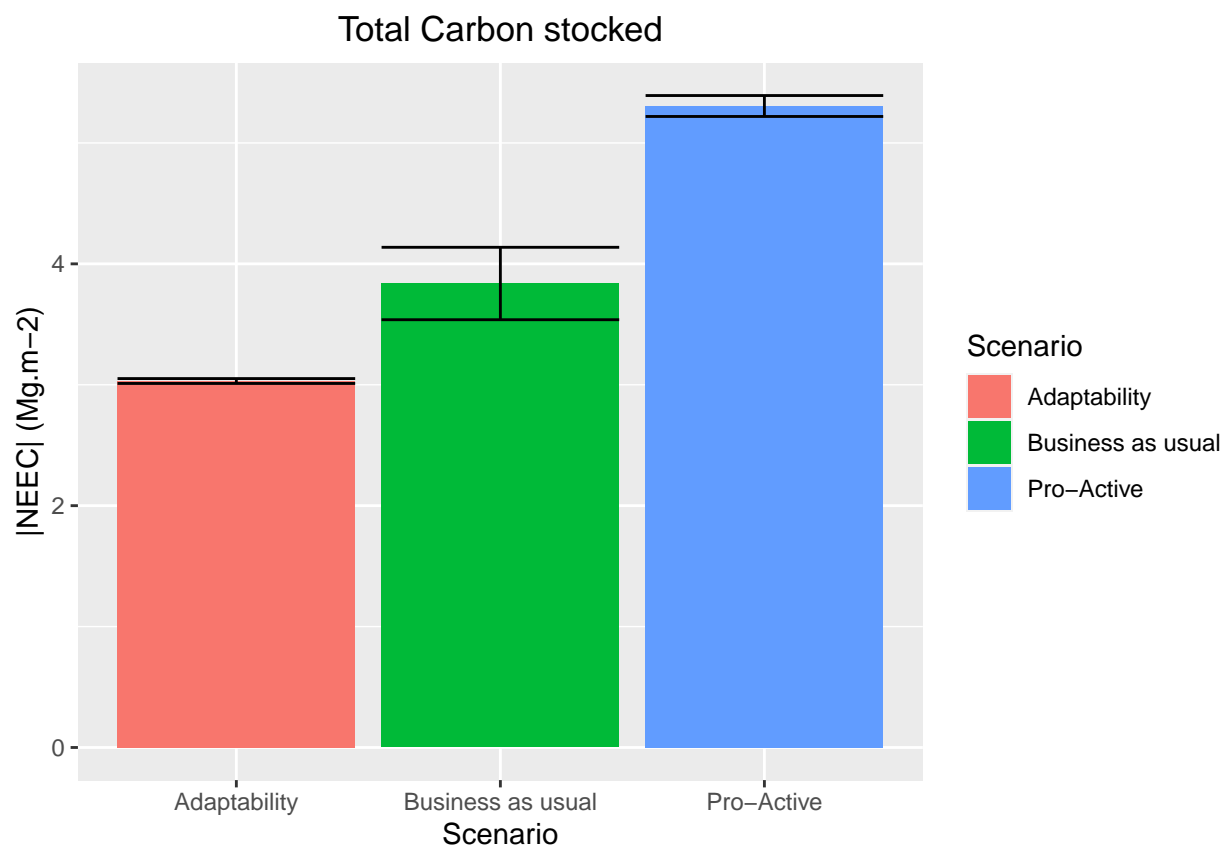


Figure 3: Total Carbon stocked

III. Resilience and disturbances regimes

III.a) Mortality due to disturbances

The biomass killed by fires that comes from lightnings (natural fire mortality), by fires coming from human activity (called here accidental fires, even if they can be intentionnal) and by insects (insect mortality) is compared on the different scenarios. To avoid an overestimation of mortality and to make sure that all the data frames have the same length, the years without insect outbreak are added with a mortality of 0. The biomass removed by harvest is also added as a mortality.

```
Mortality = data.frame()

for(j in c(1,2)){

  if(j == 1) { run = "..1"
  } else { run = "..2"}

  for(scenario in ListScenario){

    if(scenario == "Business as usual") {Input = BAU_input
    } else if(scenario == "Adaptability"){Input = Adapty_input
    } else {Input = ProAct_input}

    BDA_Tot = paste0(Input, run, "/bda_log.csv") %>% read.csv()
    BDA = cbind(BDA_Tot$Time, BDA_Tot$TotalBiomassMortality) %>% as.data.frame()
    colnames(BDA) = c("Time", "Mortality")

    BDA = aggregate(BDA$Mortality, by=list(Time=BDA$Time), FUN=sum)

    colnames(BDA) = c("Time", "Mortality")
    BDA$Mortality = BDA$Mortality*10-6 # conversion g/m2 to Mg/m2

    for(i in (1:100)){ # years without insect outbreak are added with a mortality of 0
      if(!(i %in% BDA$Time)){
        BDA = rbind(BDA, c(i,0))
      }
    }

    BDA$Disturbance = "Insects"
    BDA$Scenario = scenario
    BDA$Run = j

    scrapple_Tot = paste0(Input, run, "/scrapple-summary-log.csv") %>% read.csv()
    scrapple_Acc = cbind(scrapple_Tot$SimulationYear,
      scrapple_Tot$TotalBiomassMortalityAccidental) %>% as.data.frame()
    colnames(scrapple_Acc) = c("Time", "Mortality")
    scrapple_Acc$Mortality = scrapple_Acc$Mortality*10-6
    scrapple_Acc$Disturbance = "Fire accidental"
    scrapple_Acc$Scenario = scenario
    scrapple_Acc$Run = j

    scrapple_Nat = cbind(scrapple_Tot$SimulationYear,
      scrapple_Tot$TotalBiomassMortalityLightning) %>% as.data.frame()
```

```

colnames(scrapple_Nat) = c("Time", "Mortality")

scrapple_Nat$Disturbance = "Fire lightning"
scrapple_Nat$Scenario = scenario
scrapple_Nat$Run = j
scrapple_Nat$Mortality = scrapple_Nat$Mortality*10-6

Harvest_Tot = paste0(Input, run, "/harvest/summary-log.csv") %>% read.csv()
Harvest = Harvest_Tot %>% group_by(Time) %>%
  summarise(TotalBiomassHarvested = sum(TotalBiomassHarvested))
colnames(Harvest) = c("Time", "Mortality")
Harvest$Mortality = Harvest$Mortality %>% as.numeric()
Harvest$Mortality = Harvest$Mortality*10-4 # conversion Mg/ha in Mg/m2
Harvest$Disturbance = "Harvest"
Harvest$Scenario = scenario
Harvest$Run = j

Mortality = rbind(Mortality, BDA, scrapple_Acc, scrapple_Nat, Harvest)
}
}

```

The obtained dataframe gives all mortality (Mg/m²) for each year, disturbance, scenario and run of the model (2 per scenario).

```

kable(as.data.frame(head(Mortality)),
      caption = "Insight of the data used concerning mortality")

```

Table 2: Insight of the data used concerning mortality

Time	Mortality	Disturbance	Scenario	Run
2	24.10189	Insects	Business as usual	1
3	3.33482	Insects	Business as usual	1
4	43.98629	Insects	Business as usual	1
5	46.18279	Insects	Business as usual	1
7	29.37651	Insects	Business as usual	1
9	65.86732	Insects	Business as usual	1

The following operations are similar to the one above. To compare the mortality between scenarios and disturbances, all the mortality of a same disturbance, on the same scenario and on for same run is added (*Mortality_Sum*). After that, a mean of the mortality calculated is obtained, using the results of the two runs. Thus, a mean of total mortality is obtained for a same disturbance and scenario (*Mortality_Agg*). In addition, the standard deviation between the runs is calculated to measure the variability of the model.

```

Mortality_Sum = Mortality %>% group_by(Disturbance, Scenario, Run) %>%
  summarise(MortalitySum = sum(Mortality))

InvBessel = (ncol(Mortality_Sum)-1)/ncol(Mortality_Sum) %>% sqrt()

Mortality_Agg = Mortality_Sum %>% group_by(Disturbance, Scenario) %>%
  summarise(MortalityMean = mean(MortalitySum),
            MortalitySd = sd(MortalitySum)*InvBessel)

```


Finally, to plot the data against time, the mean and standard deviation are calculated for each year. The operations are done in the same way than above. As the evolution in time is interesting only for the harvest mortaily analyses, all others disturbances are previously merged.

```
Mortality_AggT = Mortality

Mortality_AggT$Disturbance[which(Mortality_AggT$Disturbance != "Harvest")] =
  "Other disturbances"

Mortality_AggT = Mortality_AggT %>% group_by(Time, Disturbance, Scenario, Run) %>%
  summarise(MortalitySum = sum(Mortality))

Mortality_AggT = Mortality_AggT %>% group_by(Time, Disturbance, Scenario) %>%
  summarise(MortalityMean = mean(MortalitySum),
            MortalitySd = sd(MortalitySum)*InvBessel)
```

A data frame with all the data necessary for the mortality analyzes is then created:

```
kable(as.data.frame(Mortality_Agg), caption = "Mortality depending on the scenario")
```

Table 3: Mortality depending on the scenario

Disturbance	Scenario	MortalityMean	MortalitySd
Fire accidental	Adaptability	5890.970	550.91846
Fire accidental	Business as usual	7609.968	310.85113
Fire accidental	Pro-Active	9771.626	2582.51683
Fire lightning	Adaptability	12049.611	753.08156
Fire lightning	Business as usual	11454.730	467.29013
Fire lightning	Pro-Active	17700.938	1887.29982
Harvest	Adaptability	14841.437	721.76408
Harvest	Business as usual	20377.740	1090.49751
Harvest	Pro-Active	27497.112	434.52848
Insects	Adaptability	1840.588	32.38530
Insects	Business as usual	2071.261	308.90681
Insects	Pro-Active	3194.351	65.28404

The mortality by disturbancy and by scenario can then be plotted. On the following sections, the disturbances will be detailed one by one.

```
ggplot(Mortality_Agg, aes(x=Disturbance, y=MortalityMean, fill = Disturbance)) +
  geom_bar(stat="identity") +
  geom_errorbar(aes(ymin=MortalityMean-MortalitySd, ymax=MortalityMean+MortalitySd)) +
  xlab("Type of Disturbance") +
  ylab("Mortality in biomass(Mg.m-2)") +
  ggtitle("Total mortality by scenario and disturbancy") +
  theme(plot.title = element_text(hjust = 0.5),
        axis.text.x = element_text(angle = 45, hjust = 1)) +
  facet_wrap(~Scenario, ncol=3)
```

To avoid repetition, the scripts performing mean and stadard deviation calculus as well as plotting figures and tables will not be shown.

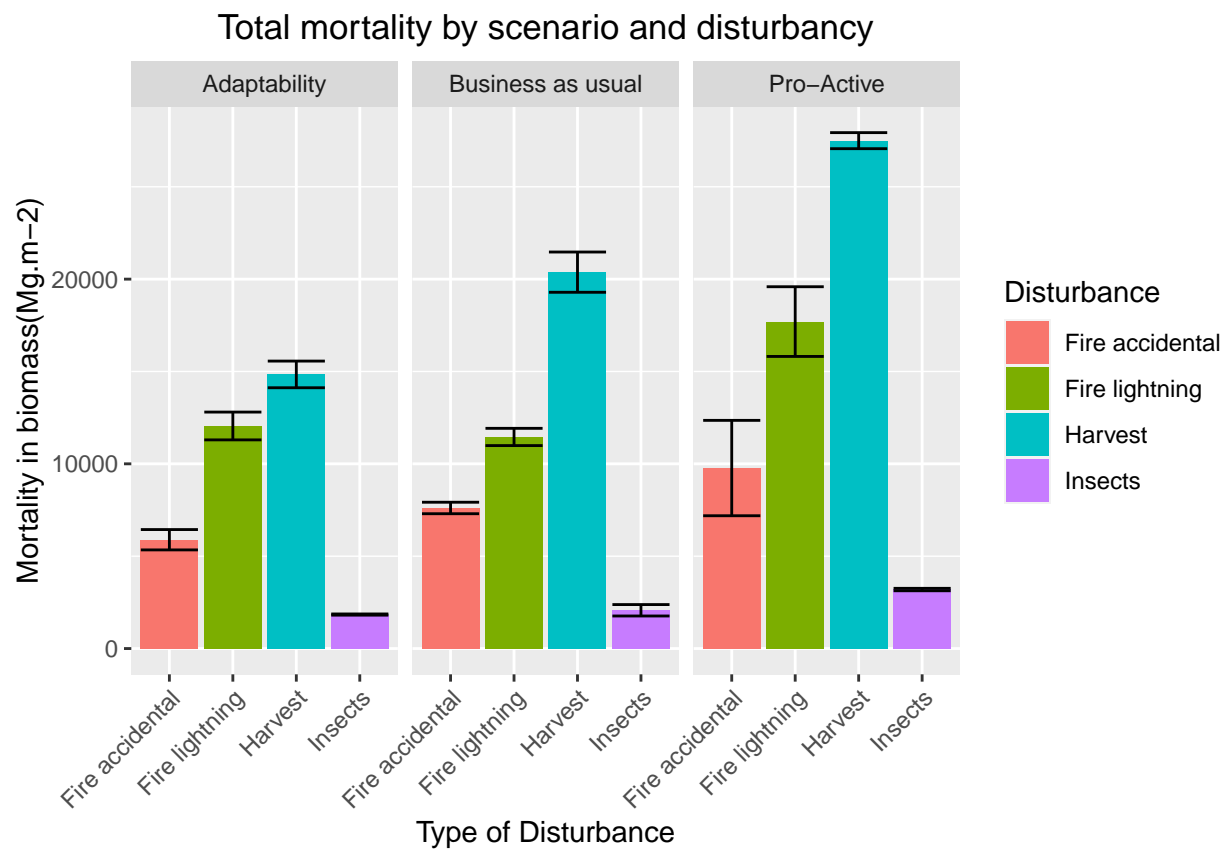


Figure 4: Total mortality by scenario and disturbancy

III.a.1) Harvest

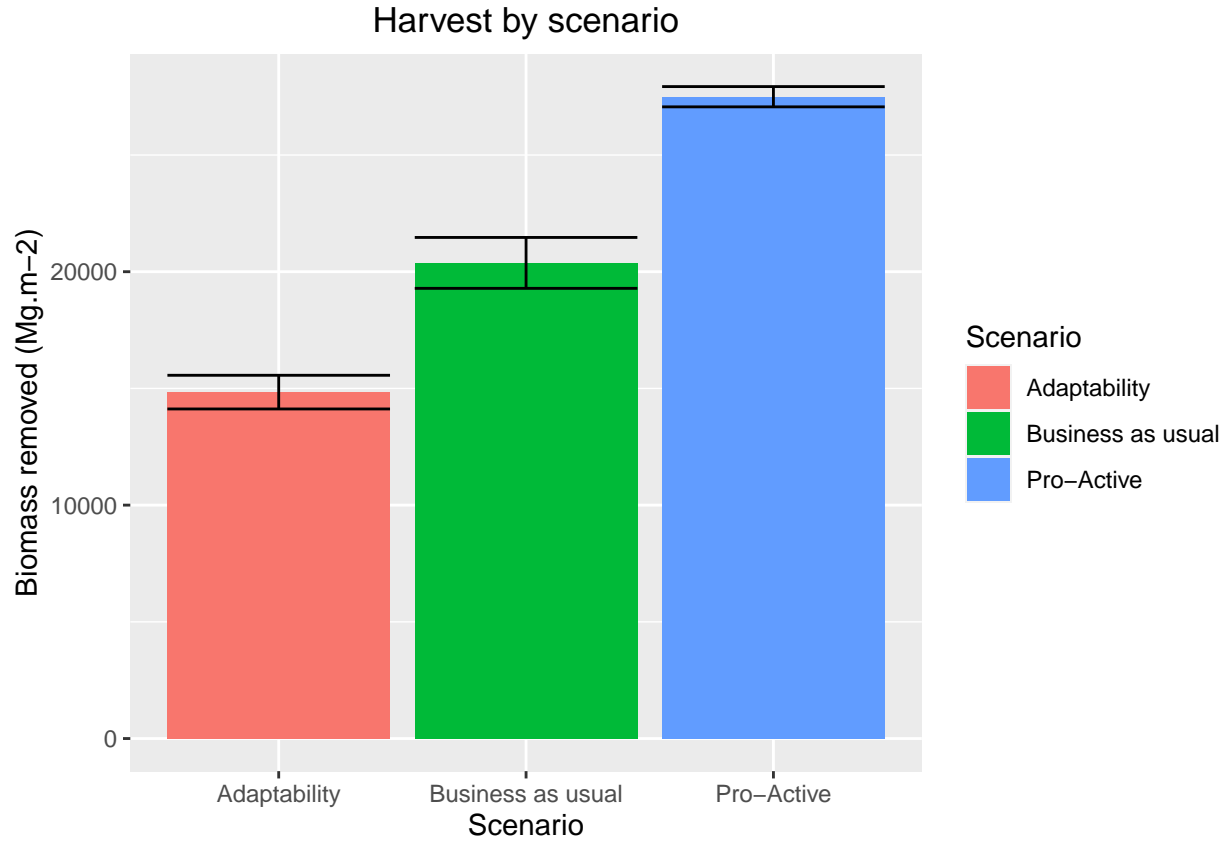


Figure 5: Harvest by scenario

Table 4: Biomass harvested depending on the scenario

Disturbance	Scenario	Mean biomass harvested (Mg.m-2)	Standard deviation inter-model
Harvest	Adaptability	14841.44	721.7641
Harvest	Business as usual	20377.74	1090.4975
Harvest	Pro-Active	27497.11	434.5285

In a similar way than the carbon stocked, the total biomass removed by harvest increases with the degree of human intervention in the scenario. This is consistent with the way the scenarios were built and validates the willingness of effort that was involved in the scenarios.

Biomass harvested was constant against time for the adaptability scenario, while it increases for the others. This reflects the previous observation, showing that maintaining a business as usual management or implementing a proactive one will lead to an increasing amount of efforts to maintain the management harvest goals.

III.a.2) Insects

Evolution of mortality due to disturbances on different scenarios

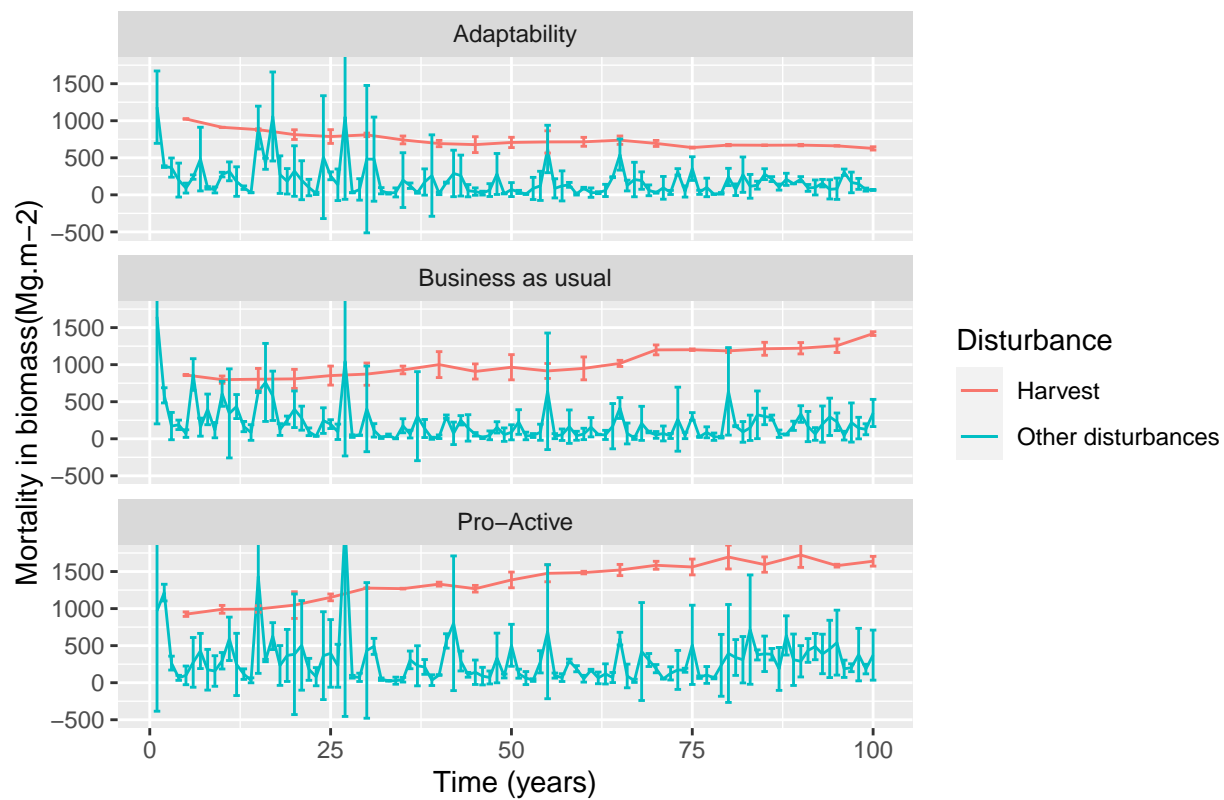


Figure 6: Evolution of mortality due to disturbances on different scenarios

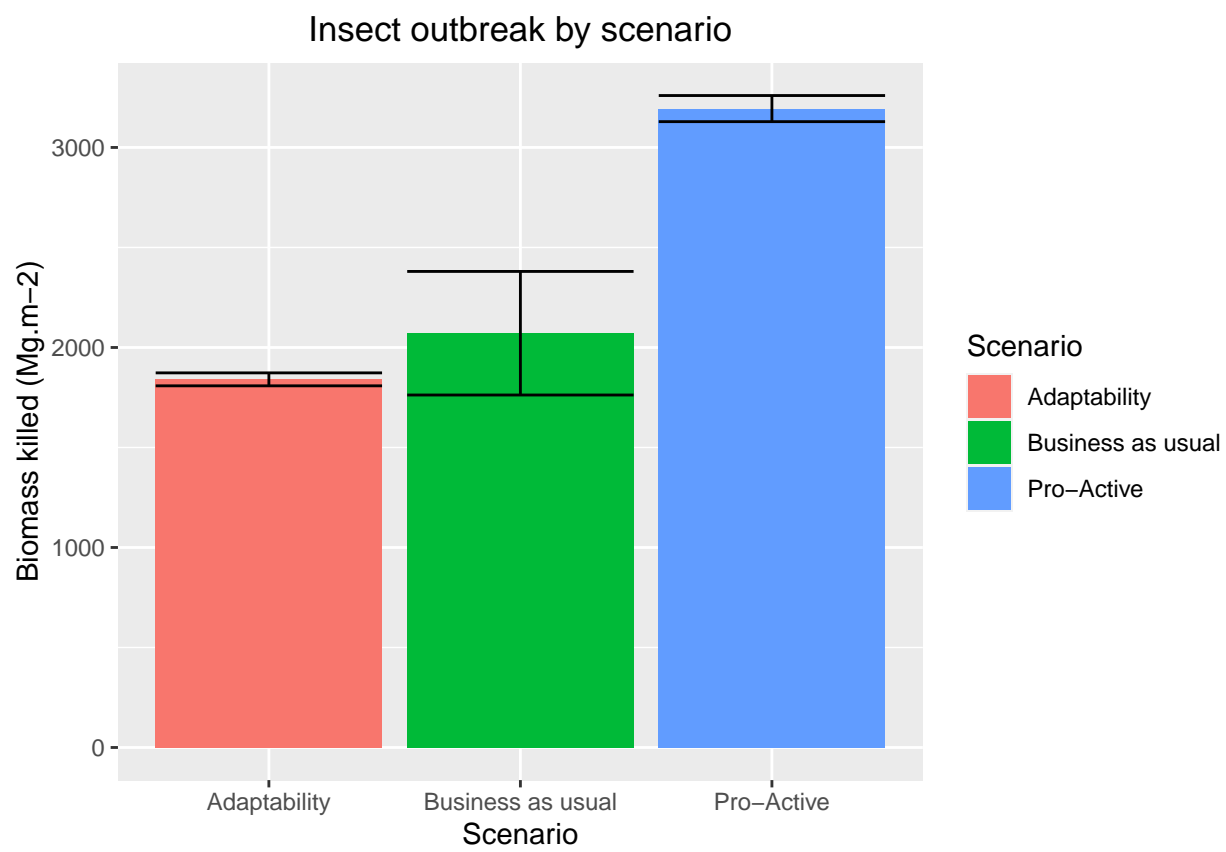


Figure 7: Insect outbreak by scenario

Table 5: Insect mortality depending on the scenario

Disturbance	Scenario	Mean mortality (Mg.m-2)	Standard deviation inter-model
Insects	Adaptability	1840.588	32.38530
Insects	Business as usual	2071.261	308.90681
Insects	Pro-Active	3194.351	65.28404

Concerning insect outbreaks, the Pro-active scenario shows mortality around 3194 Mg/m² compared to the 1840 Mg/m² and 2071 Mg/m² of respectively the Adaptability and BAU scenarios. The standard deviation bars of these two last scenarios are totally overlaid so BAU and Adaptability scenarios seem to have the same effect on insect behavior. The Pro-active scenario should not to be used if facing insect outbreaks is a priority.

III.a.3) Fire

There is no prescribed fire setted on the SCRPPLE extention, so accidental and natural fires are the only types of fire.

i) Accidental

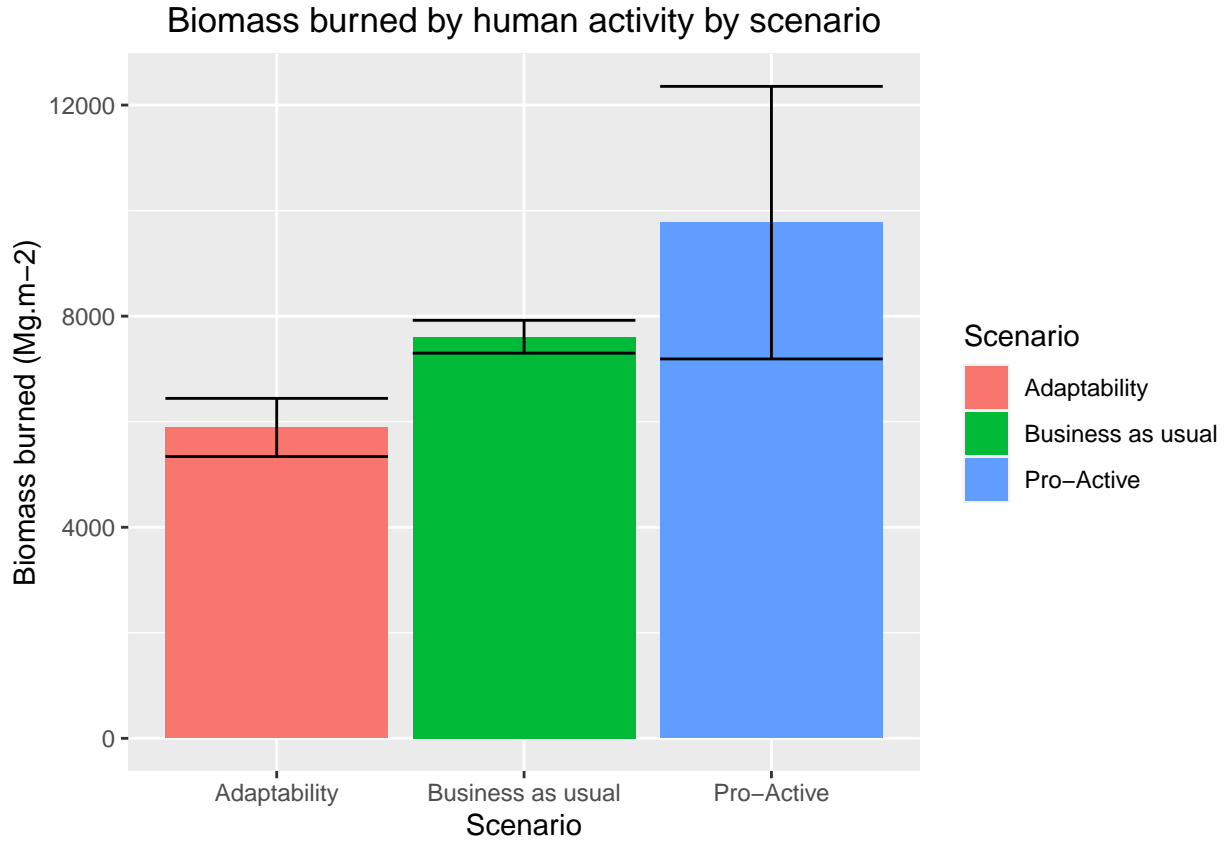


Figure 8: Biomass burned by human activity by scenario

Table 6: Accidental fire mortality depending on the scenario

Disturbance	Scenario	Mean mortality (Mg.m-2)	Standard deviation inter-model
Fire accidental	Adaptability	5890.970	550.9185
Fire accidental	Business as usual	7609.968	310.8511
Fire accidental	Pro-Active	9771.626	2582.5168

ii) Natural

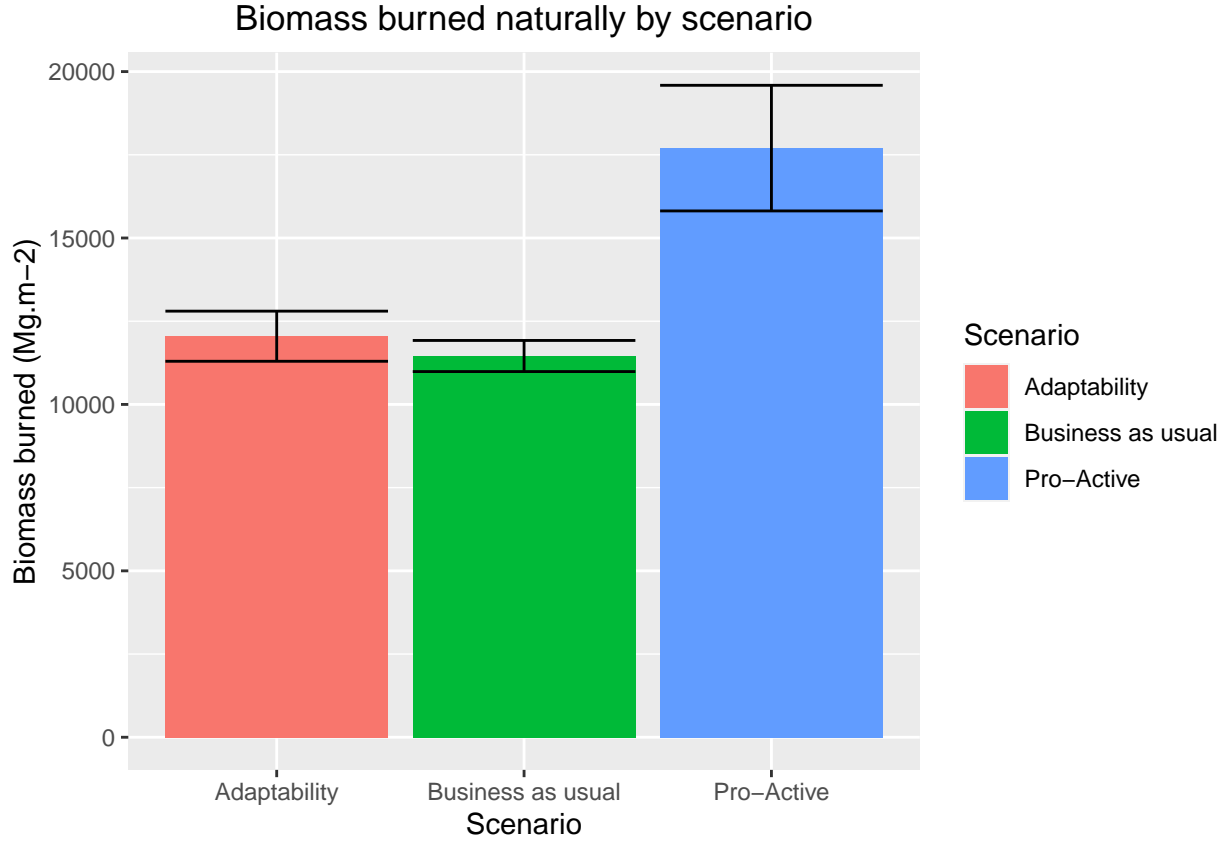


Figure 9: Biomass burned naturally by scenario

Table 7: Natural fire mortality depending on the scenario

Disturbance	Scenario	Mean mortality (Mg.m-2)	Standard deviation inter-model
Fire lightning	Adaptability	12049.61	753.0816
Fire lightning	Business as usual	11454.73	467.2901
Fire lightning	Pro-Active	17700.94	1887.2998

Burned biomass is similar between the adaptability and the BAU scenario (respectively 12050 and 11455 Mg/m²). The Pro-active scenario in contrast leads to an important amount of burned biomass (17701 Mg/m²).

III.b) Spatial distribution of the fires

To see where this increased amount of fires appears, the fire intensity (approached by the biomass burned) and fire frequency (approached by the number of years with fires).

III.b.1) Data preparation

The method is explained below. All the obtained layers are first stocked on different RasterStacks. The Quantity of biomass burned in *RasterStack_Burn*, the number of years with at least a fire in *RasterStack_AllF* for all types of fire, in *RasterStack_AccF* for accidental fires and in *RasterStack_NatF* for natural ones.

```
# Raster of zeros with the proper definition and extent
Zero = paste0(BAU_input, "..1/scrapple-fire/flaming-consumptions-1.img") %>% raster()
Zero[Zero != 0] = 0

# Empty sets where the information will be stacked
RasterStack_Burn = stack()
RasterStack_AllF = stack()
RasterStack_AccF = stack()
RasterStack_NatF = stack()

for(j in c(1,2)){

  if(j == 1) { run = "..1"
} else { run = "..2"}

  for(scenario in ListScenario){
    # When changing a scenario, the input file change
    # and the total burned and frequency scenarios are initialised to 0
    if(scenario == "Business as usual") {
      Input = BAU_input
      TotBurn = Zero
      FreqAllT = Zero
      FreqAcc = Zero
      FreqNat = Zero
    } else if(scenario == "Adaptability"){
      Input = Adapty_input
      TotBurn = Zero
      TotBurn = Zero
      FreqAllT = Zero
      FreqAcc = Zero
      FreqNat = Zero
    } else {
      Input = ProAct_input
      TotBurn = Zero
      TotBurn = Zero
      FreqAllT = Zero
      FreqAcc = Zero
      FreqNat = Zero}

    for (i in 1:100) {
      # The total burned biomass is the biomass burned the previous years
      # added to the flaming and smolder consumptions of the ongoing year
```



```

Raster_fc = paste0(Input, run, "/scrapple-fire/flaming-consumptions-",i,".img") %>%
  raster()
Raster_sm = paste0(Input, run, "/scrapple-fire/smolder-consumption-",i,".img") %>%
  raster()
RasterBurn = (Raster_fc + Raster_sm) %>% multiply_by(10^-6)
TotBurn = TotBurn + RasterBurn

Raster_FT = paste0(Input, run, "/scrapple-fire/ignition-type-",i,".img") %>%
  raster()
Raster_FT[Raster_FT == 1] = 0 # the unburned area (map code 1) is not considered here

# The sum of all types of fires is the zones where a fire append the previous years
# (all the types of fire takes the map code 1), added to the zones of the ongoing year
Raster_AllT = Raster_FT
Raster_AllT[Raster_AllT != 0] = 1
FreqAllT = FreqAllT + Raster_AllT

# The same is done with accidental fires
# (initial map code 2 turned to 1, all the rest 0)
Raster_Acc = Raster_FT
Raster_Acc[Raster_Acc == 2] = 1
Raster_Acc[Raster_Acc != 1] = 0
FreqAcc = FreqAcc + Raster_Acc

# Idem with natural fires
Raster_Nat = Raster_FT
Raster_Nat[Raster_Nat == 3] = 1
Raster_Nat[Raster_Nat != 1] = 0
FreqNat = FreqNat + Raster_Nat

if(i==100){

  # The total after the 100 years of run is saved
  TotBurn[TotBurn == 0] = NA
  names(TotBurn) = paste0(scenario, run)
  RasterStack_Burn = stack(RasterStack_Burn, TotBurn)

  FreqAllT[FreqAllT == 0] = NA
  FreqAllT = FreqAllT
  names(FreqAllT) = paste0(scenario, run)
  RasterStack_AllF = stack(RasterStack_AllF, FreqAllT)

  FreqAcc[FreqAcc == 0] = NA
  FreqAcc = FreqAcc
  names(FreqAcc) = paste0(scenario, run)
  RasterStack_AccF = stack(RasterStack_AccF, FreqAcc)

  FreqNat[FreqNat == 0] = NA
  FreqNat = FreqNat
  names(FreqNat) = paste0(scenario, run)
  RasterStack_NatF = stack(RasterStack_NatF, FreqNat)

}

```

```

    }
  }
}

```

III.b.2) Biomass burned

The results of the two simulations of a same scenarios are stacked together.

```

BAU_Burn = stack(RasterStack_Burn$Business.as.usual..1,
                 RasterStack_Burn$Business.as.usual..2)
Adapty_Burn = stack(RasterStack_Burn$Adaptability..1, RasterStack_Burn$Adaptability..2)
ProAct_Burn = stack(RasterStack_Burn$Pro.Active..1, RasterStack_Burn$Pro.Active..2)

```

Mean and stadard deviation calculations are adapted to raster layers.

```

BAU_BurnMean = calc(BAU_Burn, fun = mean)
names(BAU_BurnMean) = "Business As Usual"

BAU_BurnSd = calc(BAU_Burn, fun = sd) %>% multiply_by(InvBessel)
names(BAU_BurnSd) = "Business As Usual"

Adapty_BurnMean = calc(Adapty_Burn, fun = mean)
names(Adapty_BurnMean) = "Adaptability"

Adapty_BurnSd = calc(Adapty_Burn, fun = sd) %>% multiply_by(InvBessel)
names(Adapty_BurnSd) = "Adaptability"

ProAct_BurnMean = calc(ProAct_Burn, fun = mean)
names(ProAct_BurnMean) = "Pro-Active"

ProAct_BurnSd = calc(Adapty_Burn, fun = mean) %>% multiply_by(InvBessel)
names(ProAct_BurnSd) = "Pro-Active"

```

To be able to compare the rasters, they are plotted using the same legend. This legend is calculated using the maximum and minimum values of all three rasters. In the present document, the breaks are choosen arbitrarily some elements are overlapping (legend, label and plots). When the layers bring important information concerning the objective of the study, they are exported to be properly presented with the software Qgis. Legends are then built using the following method: first, a visualisation of the BAU scenario (used as a referency) is realised using the equal intervals setting. This option as it allows to identify localised extreme values unlike a visualisation by quantiles. By testing, I found that 6 intervals allows to see the interesting information without overloading the map. The breaks obtained are rouded for a better lengend visibility. This breaks are then used for the others scenarios, making comparison of maps also possible.

```

VarStack = stack(BAU_BurnMean, Adapty_BurnMean, ProAct_BurnMean)
Max = max(maxValue(VarStack))
Min = min(minValue(VarStack))
brks = seq(Min,Max,by=0.01)
nbrks = length(brks)-1
r.range = c(Min, Max)

```

```

rasTot = raster(ncol=2, nrow=1)
values(rasTot) = c(Min,Max)

par(mfrow=c(1,3), mar=c(4.1, 0, 4.1, 10.1))

plot(VarStack, breaks=brks,col=pal.3(nbrks), legend = F,
     main=names(VarStack),zlim=c(Min,Max),)
plot(rasTot, legend.only=TRUE, col=pal.3(nbrks),
     legend.width=1, legend.shrink=0.75,
     legend.args=list(text="Burned biomass (Mg.m-2)",
                      side=4, font=2, line=2.5, cex=0.8))

```

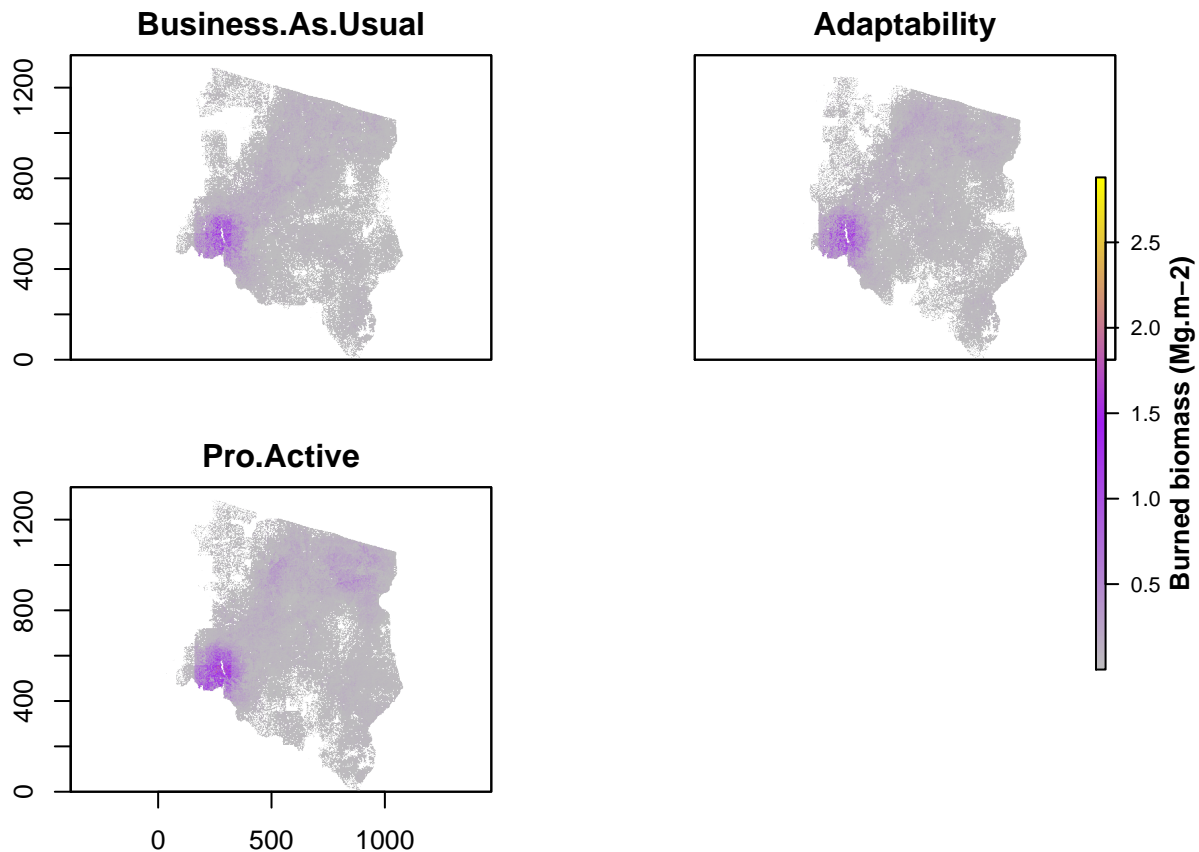


Figure 10: Total burned biomass by scenario

An important amount of biomass burned is observed on the southwestern part of the Klamath region. This behavior is hard to explain.

```

VarStack = stack(BAU_BurnSd, Adapty_BurnSd, ProAct_BurnSd)
Max = max(maxValue(VarStack))
Min = min(minValue(VarStack))
brks = seq(Min,Max,by=0.01)
nbrks = length(brks)-1
r.range = c(Min, Max)
rasTot = raster(ncol=2, nrow=1)
values(rasTot) = c(Min,Max)

```

```

par(mfrow=c(1,3), mar=c(4.1, 0, 4.1, 10.1))

plot(VarStack, breaks=brks,col=pal.sd(nbrks), legend = F,
     main=names(VarStack),xlim=c(Min,Max),)
plot(rasTot, legend.only=TRUE, col=pal.sd(nbrks),
     legend.width=1, legend.shrink=0.75,
     legend.args=list(text="Standard error on burned biomass (Mg.m-2)",
                       side=4, font=2, line=2.5, cex=0.8))

```

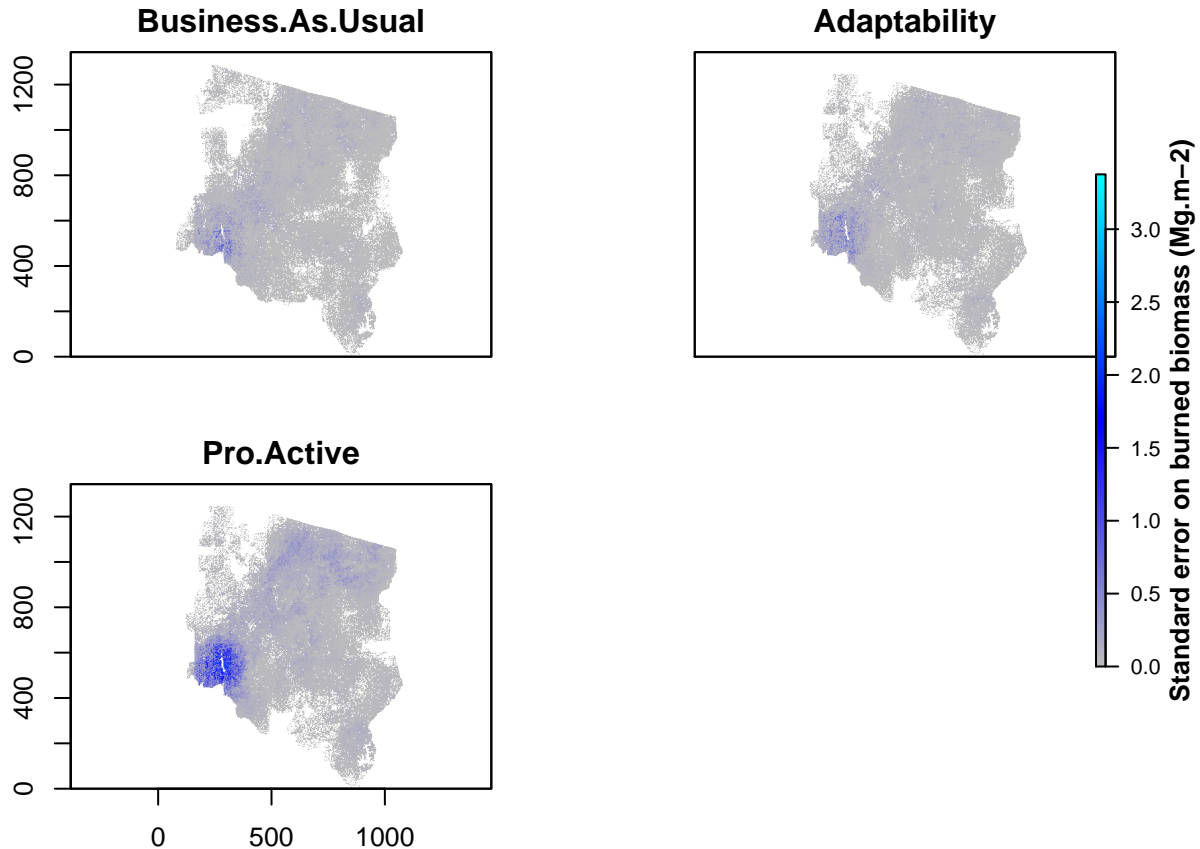


Figure 11: Standard deviation of Burned biomass by scenario

Variability is important, but mostly concentrated in the curious southwestern part of the Klamath region.

III.b.3) Number of years with fires

ToThe number of years with at least a fire is plotted for each cell. The same operations than before are done to determine mean values and their standard deviation and for plotting them. The corresponding code is not shown to avoid redundancy.

- i) All types of fires

If the southwestern part still have unexpected and unexplained intense fire frequency, the northeastern part shows more interesting variations of frequency between the scenarios. To have more detail, the

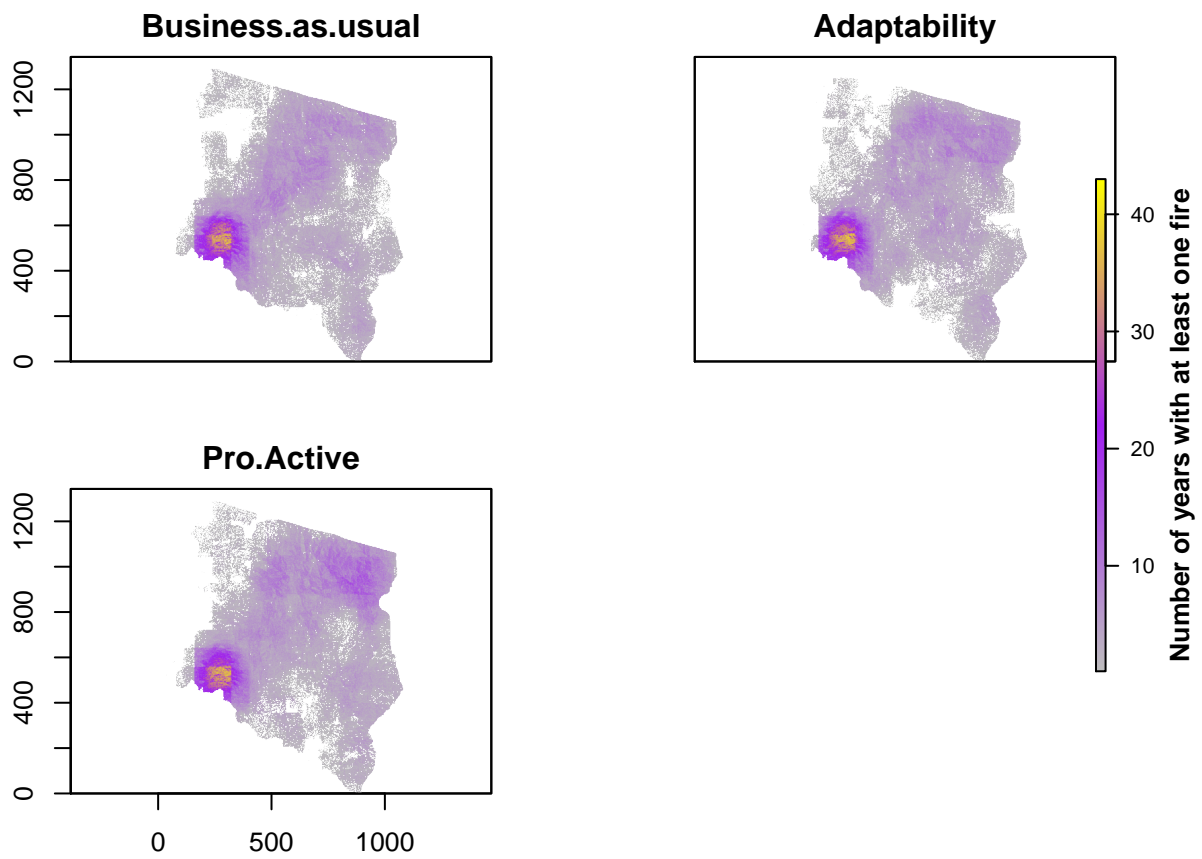


Figure 12: Number of fire years by scenario

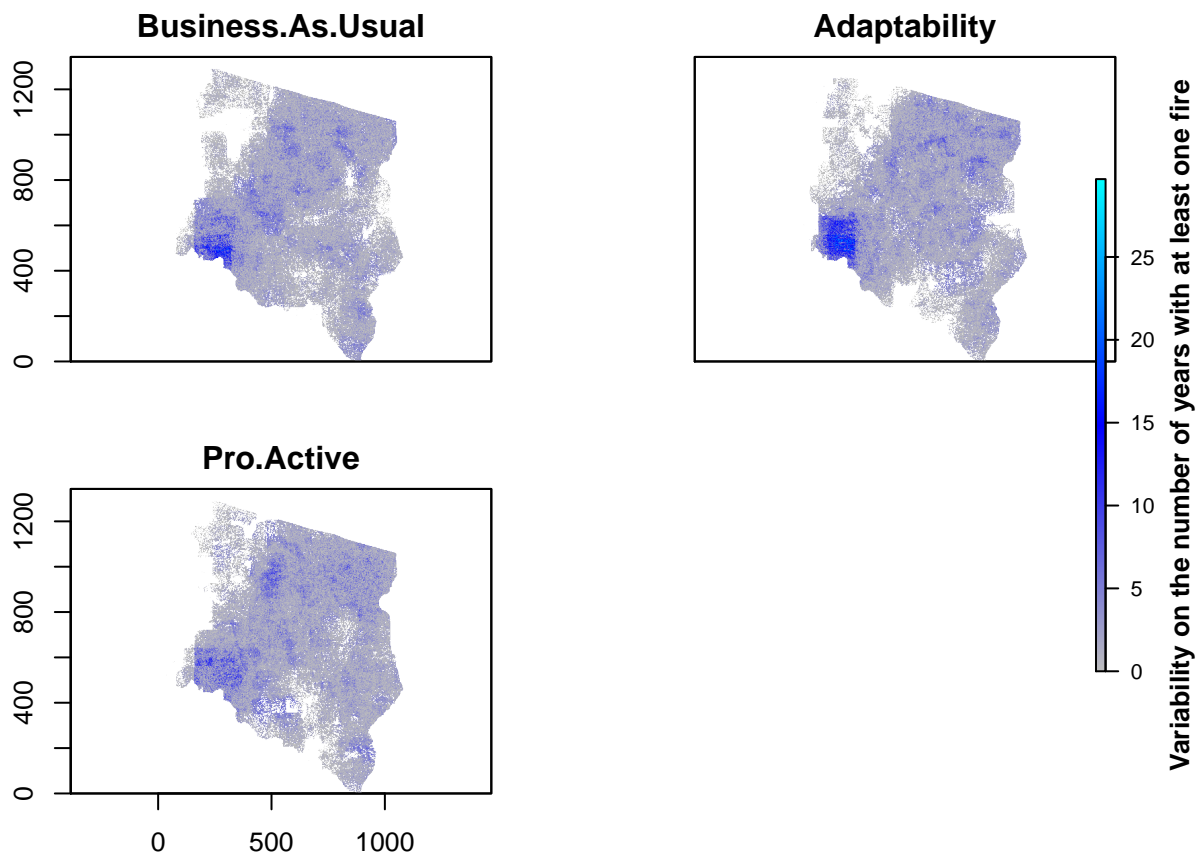


Figure 13: Standard deviation in fire years

Variability seems equally distributed, except for the southwestern part of the map. For more detail, the same plots are done for natural and accidental fires.

ii) Fires initiated by humans

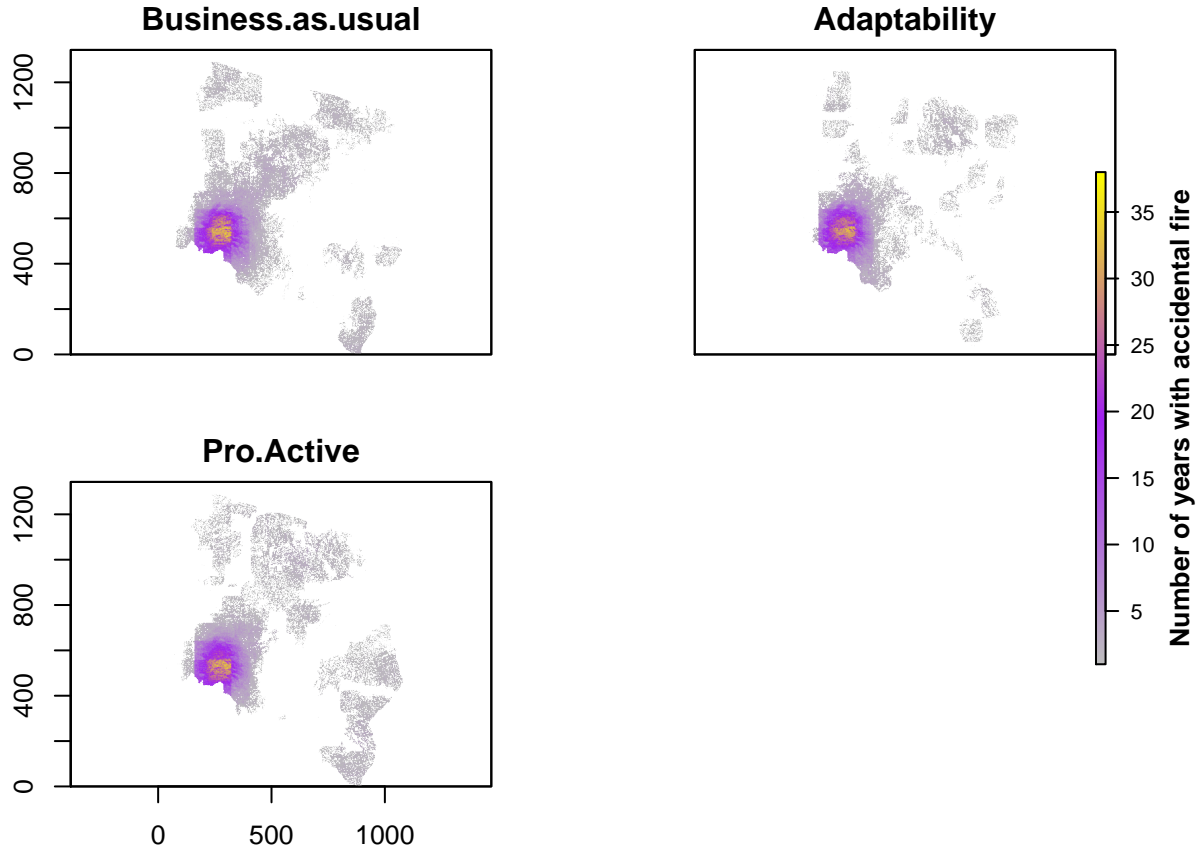


Figure 14: Number of accidental fire years by scenario

iii) Fires initiated by lightning

The unexplained fire behavior of the southwestern part of the map seems to be originated by the simulation of accidental fires. As this can be due to an error of modeling (according to the expert Dr.Robert Scheller) and need further verification before interpretation, only natural fires are then analyzed. There is an increase in the North East of the Klamath region that isn't observed for the other scenarios. This zone doesn't correspond to the Resistance prescription, so the important frequency of fires is explained by the plantations. This result shows that, despite efforts of management for fire risk, intense plantations can lead to an increase of fires, and that may waste investments.

VI. Forest sustainability and biodiversity

VI.a) Sustainability of the forest

The biomass and forest cover results are computed at the same time. Rasters concerning shrubs biomass are imported for the year 0 and 100 and added together (respectively *Shrub0* and *Shrub100*). The total

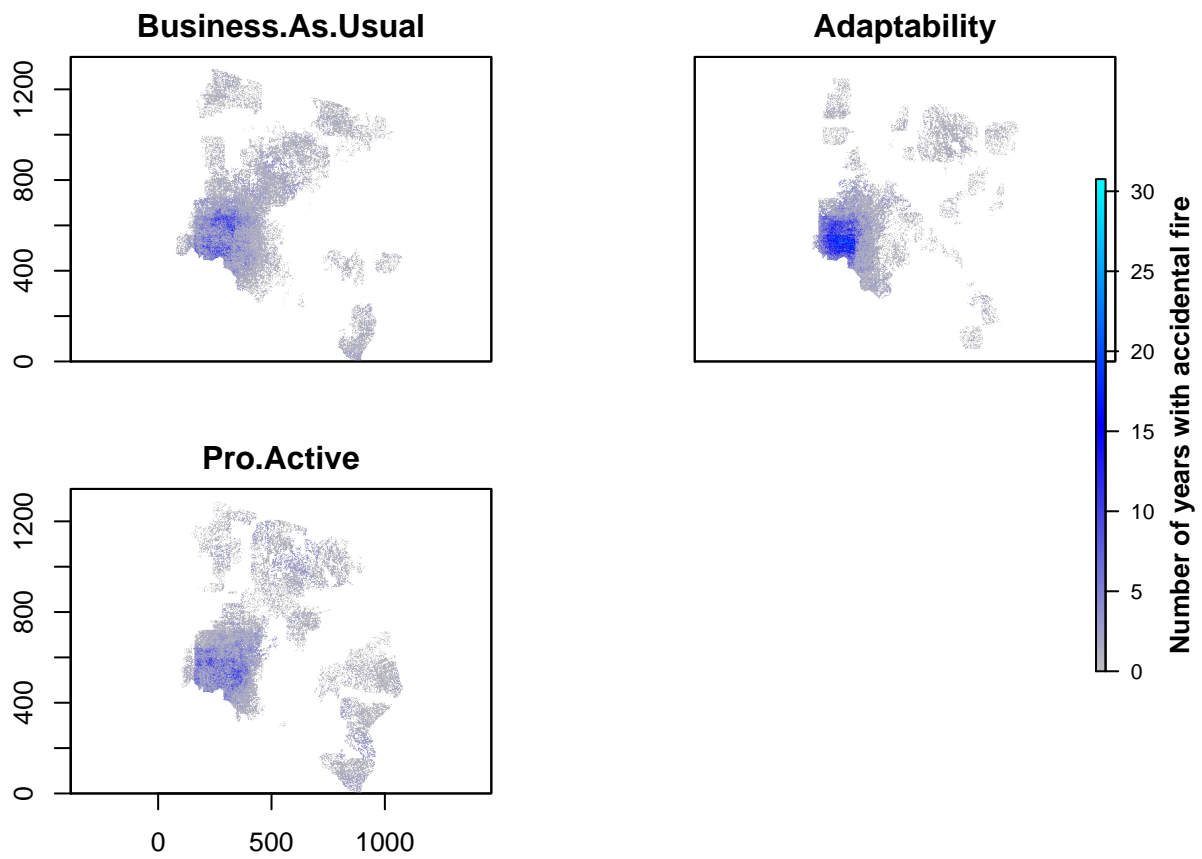


Figure 15: Standard deviation on accidental fire years

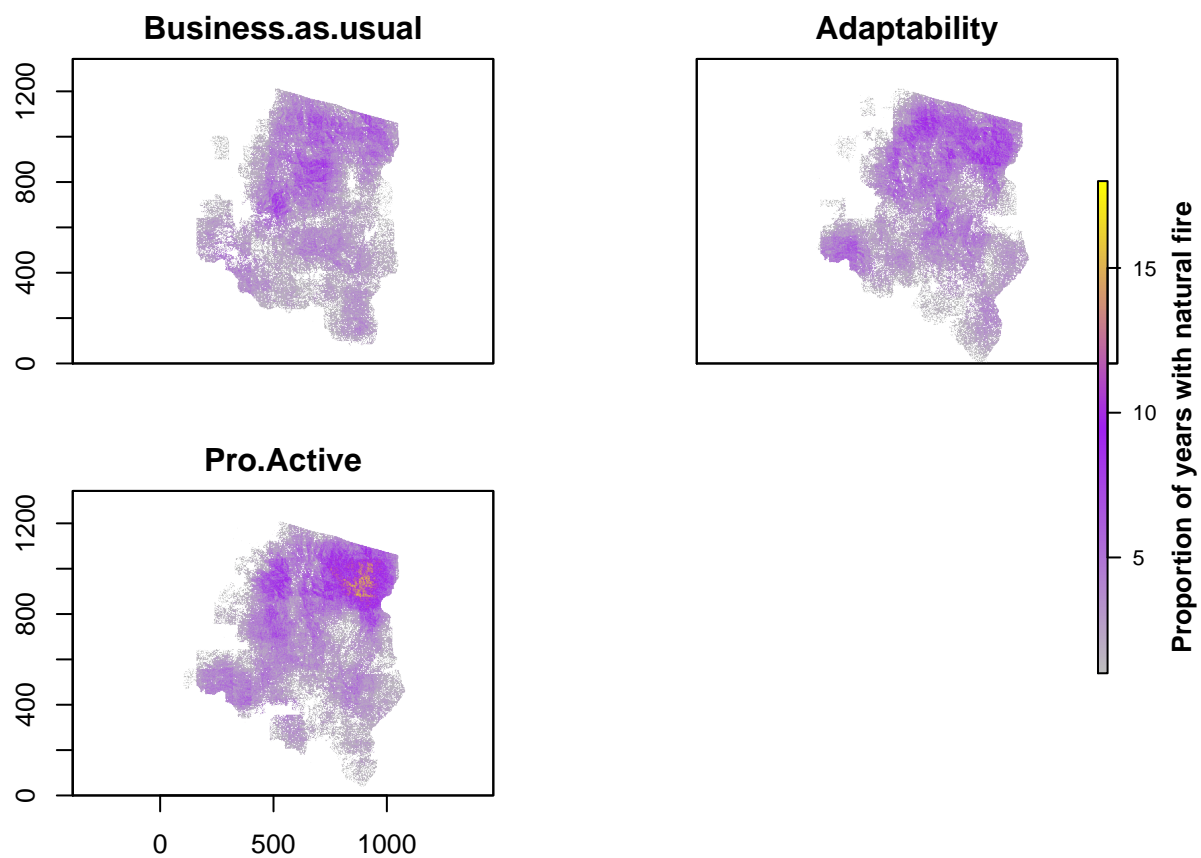


Figure 16: Number of natural fire years by scenario

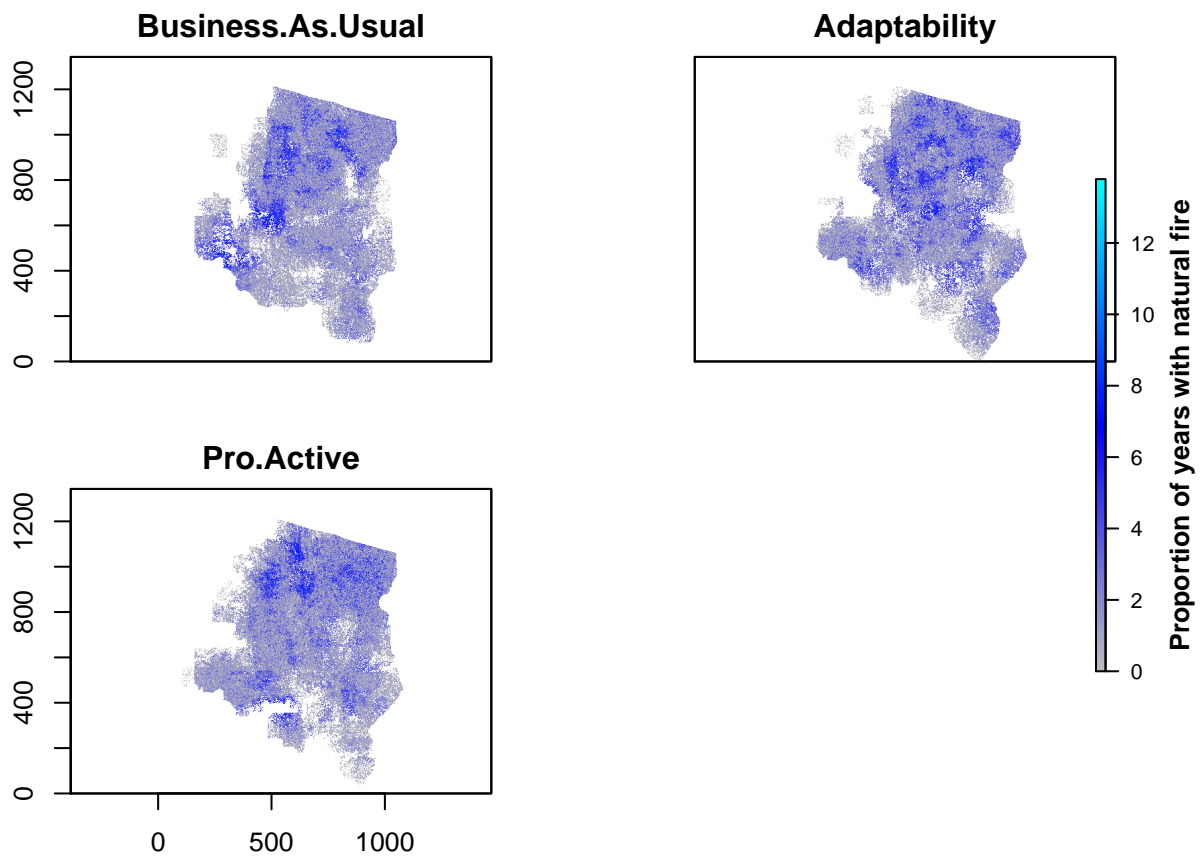


Figure 17: Standard deviation on accidental fire years

biomass, *i.e.* the biomass of all species, is also imported ($BMTot0$ and $BMTot100$). The biomass evolution is obtained by making the difference between the initial and final biomass. For the forest cover, the operation is done by the equation 3.

Equation 3:

$$\Delta FC_i = FC_{100,i} - FC_{0,i}$$

$$\Leftrightarrow \Delta FC_i = 100 \left(1 - \frac{BM_{s100,i}}{BM_{100,i}} \right) - 100 \left(1 - \frac{BM_{s0,i}}{BM_{0,i}} \right)$$

With:

- ΔFC_i the forest cover evaluation for the scenario $i \in [Businessasusual, Adaptability, Proactive]$. It correspond to the evolution of the proportion of trees on the biomass (in percentage).
- $FC_{100,i}$ and $FC_{0,i}$ respectively the final and initial forest cover for the scenario i .
- $BM_{s100,i}$ and $BM_{s0,i}$ respectively the final and initial biomass of shrubs for the scenario i .
- $BM_{100,i}$ and $BM_{0,i}$ respectively the final and initial total biomass (shrubs and trees) for the scenario i .

```
StackCovDif = stack()
StackBM0 = stack()
StackBM100 = stack()
StackBMdiff = stack()

for(j in c(1,2)){
  if(j == 1) { run = "..1"
  } else { run = "..2"}

  for(scenario in ListScenario){

    if(scenario == "Business as usual") {Input = paste0(BAU_input,run,"/biomass/")
    } else if(scenario == "Adaptability"){Input = paste0(Adapty_input,run,"/biomass/")
    } else {Input = paste0(ProAct_input,run,"/biomass/")}

    FxR0 = paste0(Input,"FX_R_SEED-0.tif") %>% raster() %>% multiply_by(10^-6)
    FxR100 = paste0(Input,"FX_R_SEED-100.tif") %>% raster() %>% multiply_by(10^-6)

    NFxR0 = paste0(Input,"NOFX_R_SEED-0.tif") %>% raster() %>% multiply_by(10^-6)
    NFxR100 = paste0(Input,"NoFX_R_SEED-100.tif") %>% raster() %>% multiply_by(10^-6)

    NFxNR0 = paste0(Input,"NOFX_NOR_SEED-0.tif") %>% raster() %>% multiply_by(10^-6)
    NFxNR100 = paste0(Input,"NoFX_NOR_SEED-100.tif") %>% raster() %>% multiply_by(10^-6)

    Shrub0 = FxR0 + NFxR0 + NFxNR0
    Shrub100 = FxR100 + NFxR100 + NFxNR100

    BMTot0 = paste0(Input,"TotalBiomass-0.tif") %>% raster() %>% multiply_by(10^-6)
    BMTot100 = paste0(Input,"TotalBiomass-100.tif") %>% raster() %>% multiply_by(10^-6)

    BMTot0[BMTot0 >= 300000] = NA

    BMdiff = BMTot100-BMTot0

    BMTot0[BMTot0 == 0] = NA
    BMTot100[BMTot100 == 0] = NA
```

```

BMdiff[BMdiff == 0] = NA

Covert0 = 1-(Shrub0/BMTot0)
Covert100 = 1-(Shrub100/BMTot100)

CovDif = (Covert100-Covert0)*100

names(CovDif) = paste0(scenario,run)
StackCovDif = addLayer(StackCovDif, CovDif)

names(BMTot0) = paste0(scenario,run)
names(BMTot100) = paste0(scenario,run)
names(BMdiff) = paste0(scenario,run)

StackBMO = addLayer(StackBMO, BMTot0)
StackBM100 = addLayer(StackBM100, BMTot100)
StackBMdiff = addLayer(StackBMdiff, BMdiff)

}
}

```

VI.a.1) Repartition of the biomass

Standard deviation of the difference in biomass is not calculated, as the known formula $s = \sqrt{s_a^2 + s_b^2}$ is valid only for independent measures.

The total biomass seems to evolve similarly on the scenarios. To verify that, the difference in biomass is plotted.

The patterns of biomass evolution seems similar. The great losses of the southwest reflect the frequent and intense fires observed previously.

VI.a.2) Evolution of the forest cover

The evolution in the proportion of trees on the biomass (here as a percentage) shows a decline in forest cover, meaning that none of the scenarios are able to tackle the increase of shrub biomass against trees. This value is outstandingly low for the Adaptability scenario, with a decrease of 19% of the biomass of trees over the total biomass. The BAU and Pro-active scenarios are both around 8%. This is surprising, as it would have been expected that the intense tree planting of the Pro-active scenario would increase the proportion of trees. This result shows that letting natural regeneration (Adaptability) is not a suitable way of regeneration in the Klamath region, as it will lead to an important domination of shrubs. They also show that intensive planting (Pro-active) is neither a solution, as the gain compared to moderate planting (BAU) is neglectable.

Table 8: Increase in trees on the total biomass (%)

mean	sd	Scenario
-9.131931	0.7029169	Business as usual
-19.300347	0.8744564	Adaptability
-7.909159	1.3068265	Pro-active

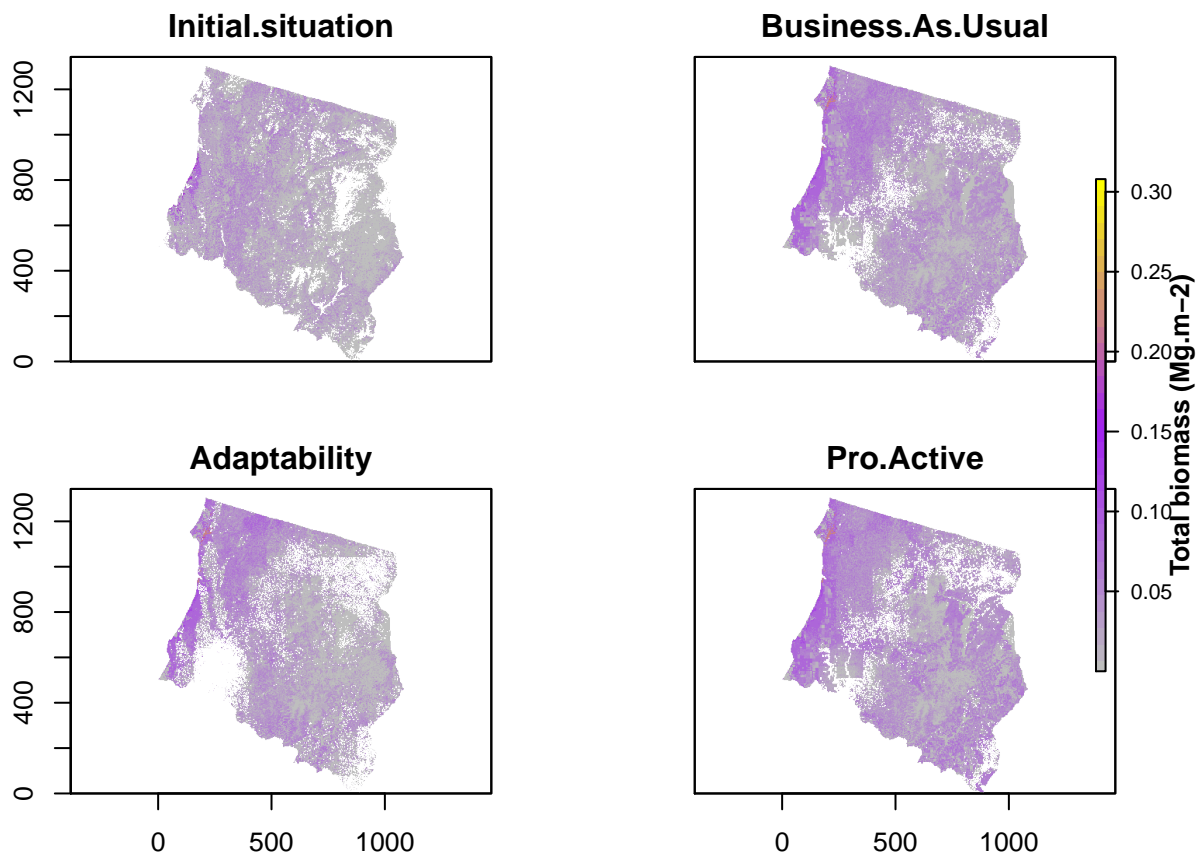


Figure 18: Above ground live biomass by scenario after 100 years

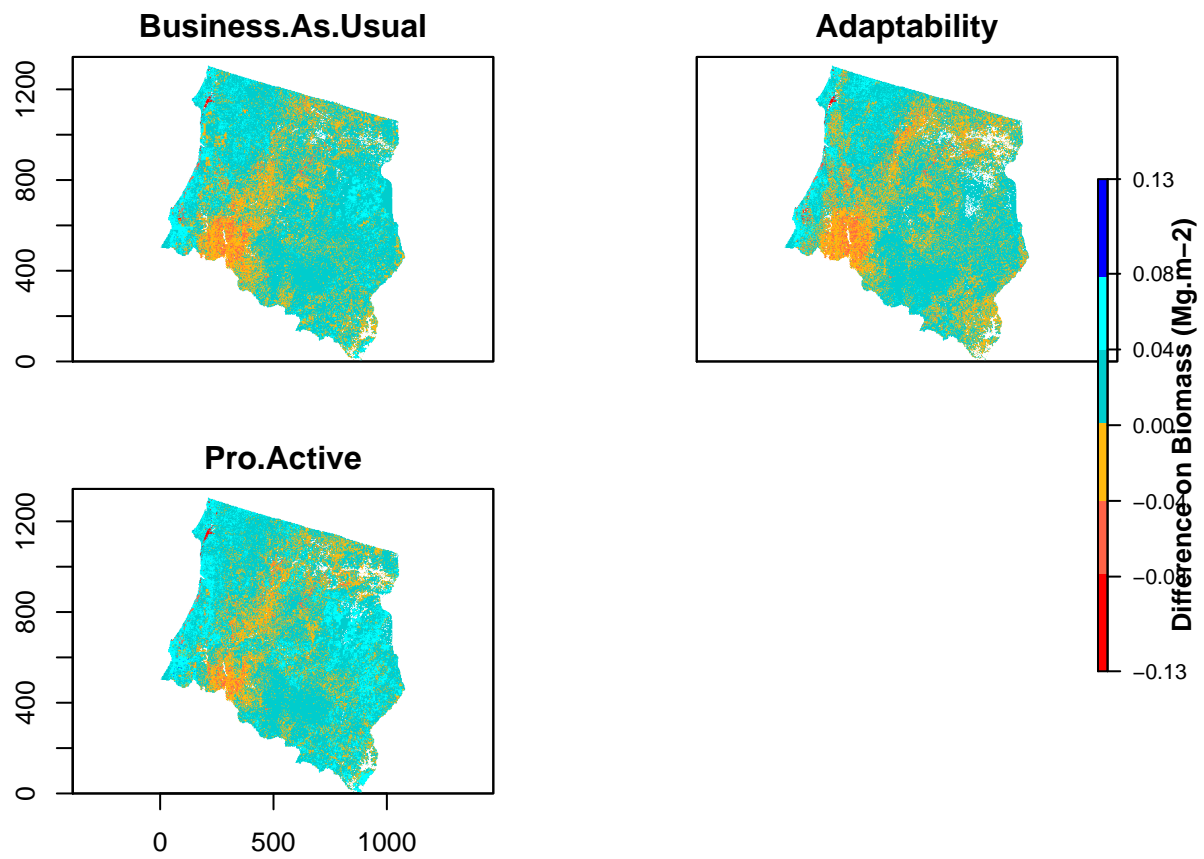


Figure 19: Evolution of above ground live biomass by scenario

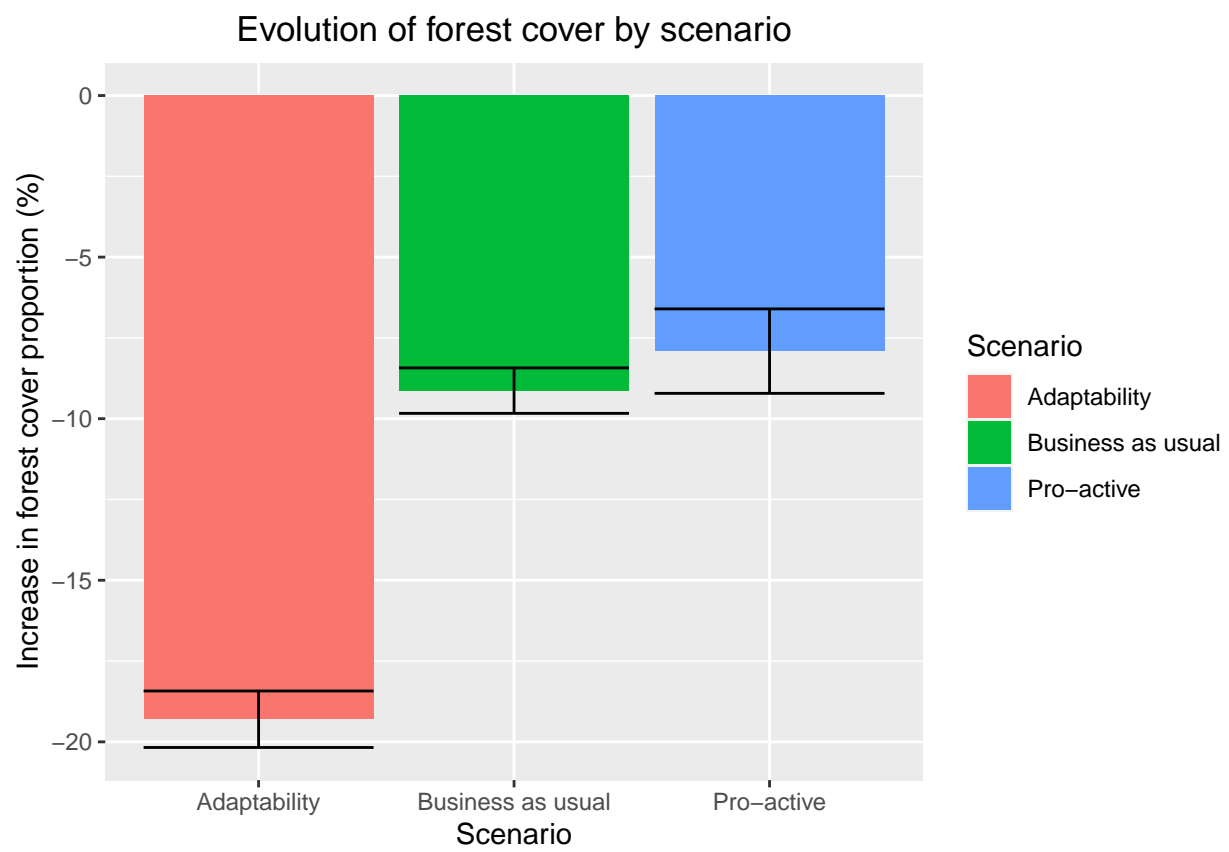


Figure 20: Evolution of forest cover by scenario

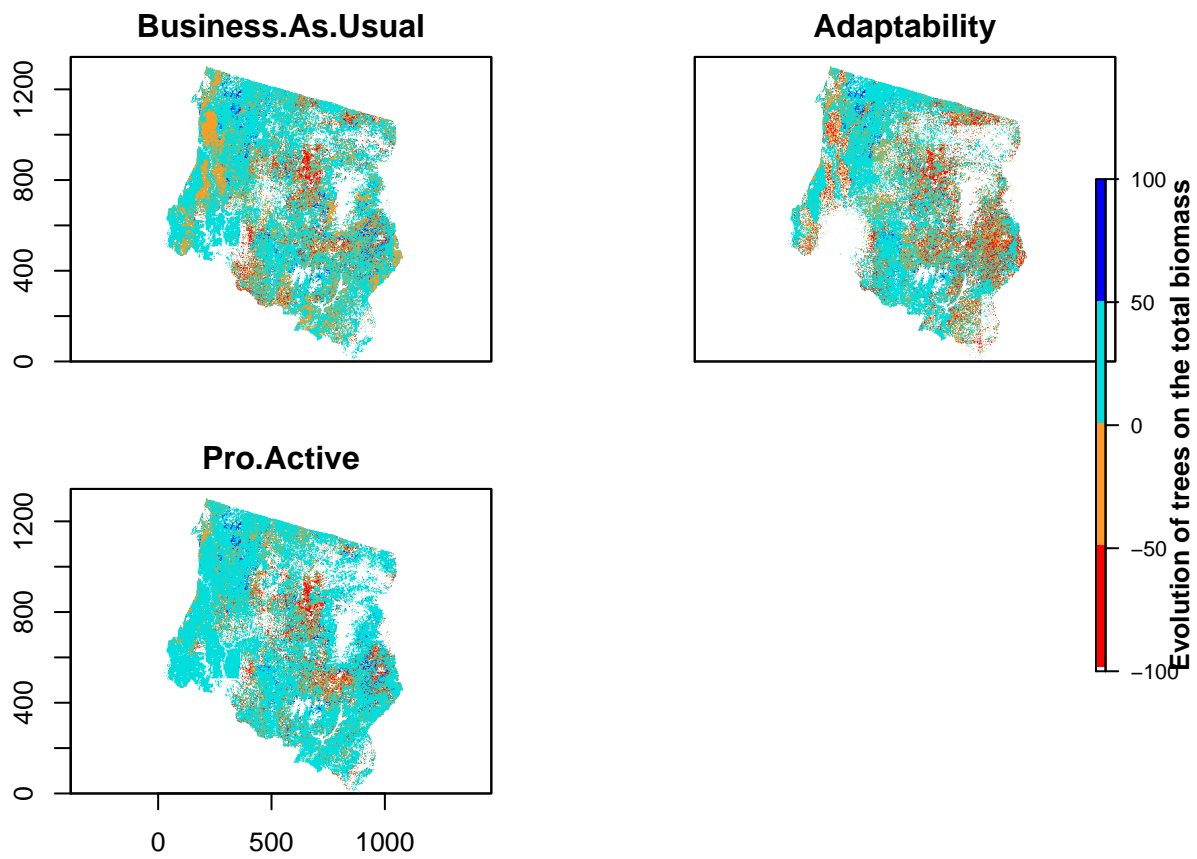


Figure 21: Evolution of the proportion of trees by scenario

VI.a.2) Regeneration

```
Rege = data.frame()

for(j in c(1,2)){

  if(j == 1) { run = "..1"
  } else { run = "..2"}

  for(scenario in ListScenario){

    if(scenario == "Business as usual") {Input = BAU_input
    } else if(scenario == "Adaptability"){Input = Adapty_input
    } else {Input = ProAct_input}

    Reprolog = paste0(Input, run, "/NECN-reproduction-log.csv") %>% read.csv()
    Reprolog$NbEvents = Reprolog$NumCohortsPlanting + Reprolog$NumCohortsSerotiny +
      Reprolog$NumCohortsResprout + Reprolog$NumCohortsSeed
    Repro = cbind(Reprolog$Time, Reprolog$NbEvents) %>% as.data.frame()
    colnames(Repro) = c("Time", "NbEvents")
    Repro$Scenario = scenario
    Repro$Run = j

    Rege = rbind(Rege,Repro)
  }
}

Rege$NbEvents = Rege$NbEvents %>% as.character() %>% as.numeric()
```

Table 9: Total number of reproduction events by scenario

Scenario	NbEventsMean	NbEventsSd
Adaptability	30086514	238469.3
Business as usual	38332074	558985.9
Pro-Active	137367768	1364338.8

The number of reproductive events follows what would have been expected. Indeed, planting is taken into account and the number of events for Pro-active (more than 137.10^6) is superior to BAU (38.10^6) itself superior to Adaptability (30.10^6).

Table 10: Total number of reproduction event (without planting)

Scenario	NbEventsMean	NbEventsSd
Adaptability	30086514	238469.3
Business as usual	27219285	628955.6
Pro-Active	28253512	1218307.2

Without taking in account planting, the results are similar to each other, with a slight superior value for the adaptability scenario. This light difference demonstrates that by planting (intensively or moderately alike)

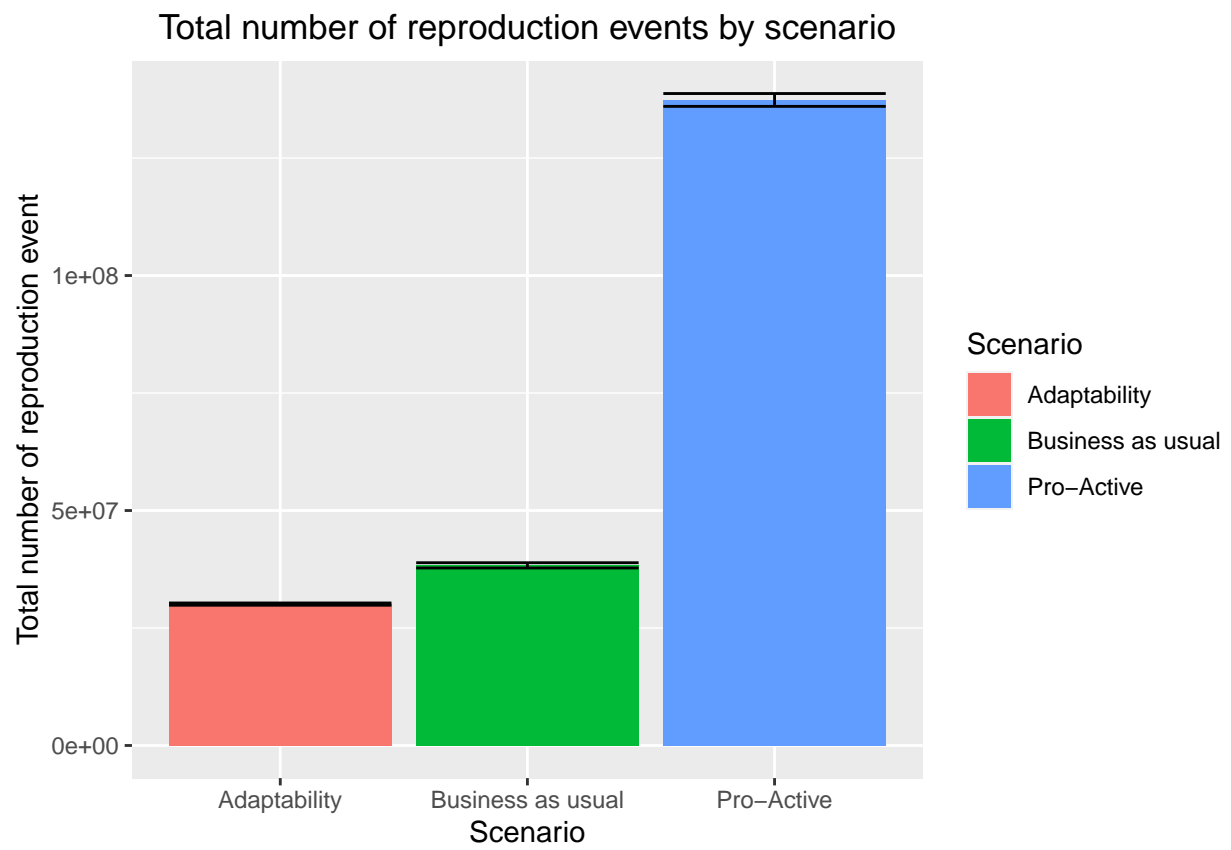


Figure 22: Total number of reproduction events by scenario

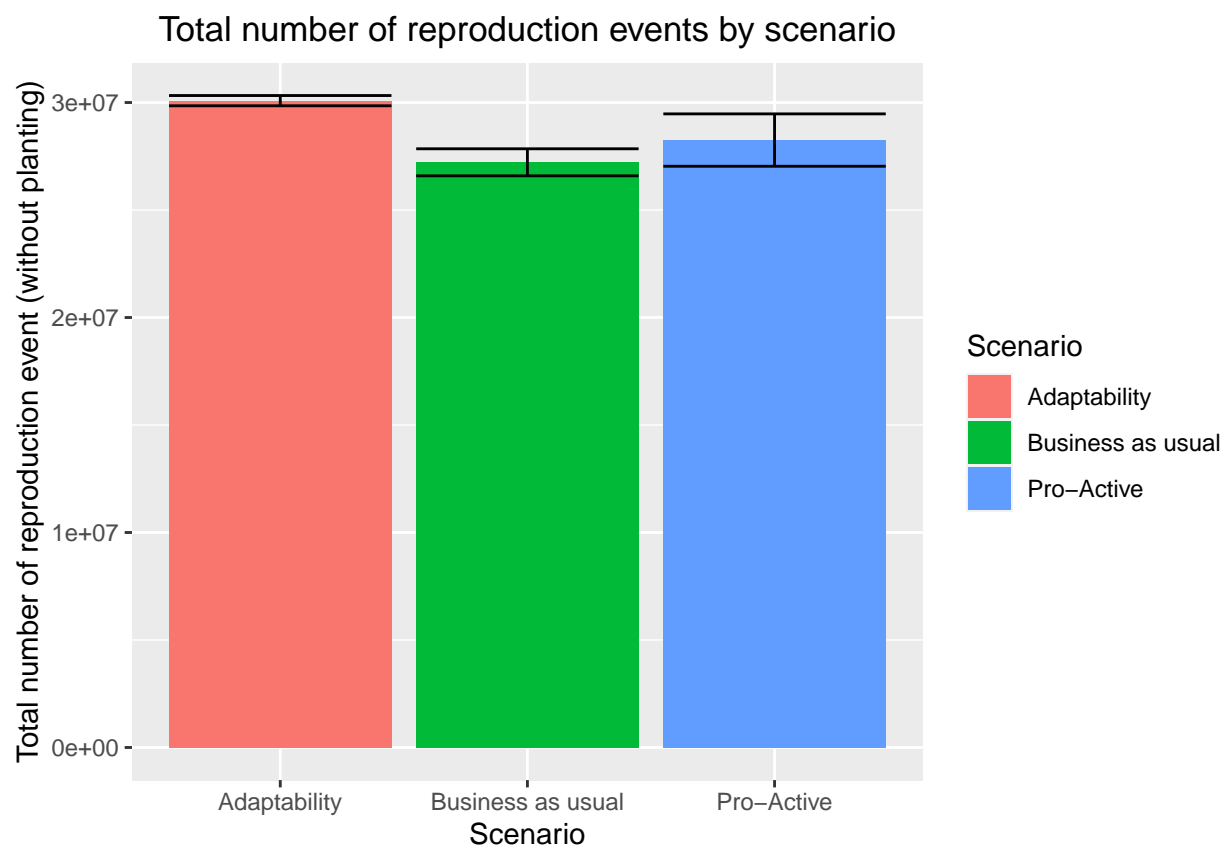


Figure 23: Total number of reproduction events by scenario

no consequent competition is done to the other forms of regeneration. Even if competition happens later in the growth process, the genetic variability that would have happened with seeding, and the advantages of sprouting and scerotiny are kept.

IV.b) Biodiversity on the forest

To measure biodiversity, species and age richness is analysed. All 10 years, the total species richness and age richness are stored on a dataframe (*Biodiv*). Initial and final maps are stored on rasterstacks.

```
Biodiv = c("Year", "Scenario", "Spp_Rich", "Age_Richness", "Run")

StackSR0 = stack()
StackSR100 = stack()

StackAR0 = stack()
StackAR100 = stack()

for(j in c(1,2)){

  if(j == 1) { run = "..1"
  } else { run = "..2"}

  for(year in seq(0, 100, by=10)){
    for(scenario in ListScenario){

      if(scenario == "Business as usual") {Input = BAU_input
      } else if(scenario == "Adaptability"){Input = Adapty_input
      } else {Input = ProAct_input}

      SppRich = paste0(Input,run,"/outputs/spp-counts/SPP-RICH-",
                        year,".img") %>% raster()
      SppRich[SppRich == 0] = NA
      SppRich_mean = cellStats(SppRich, stat='mean', na.rm=TRUE)

      AgeRichness = paste0(Input,run,"/outputs/age-all-spp/AGE-RICH-",
                            year,".img") %>% raster()
      AgeRichness[AgeRichness == 0] = NA
      AgeRichness_mean = cellStats(AgeRichness, stat='mean', na.rm=TRUE)

      if(year == 0){

        names(SppRich) = paste0(scenario,run)
        StackSR0 = addLayer(StackSR0, SppRich)

        names(AgeRichness) = paste0(scenario,run)
        StackAR0 = addLayer(StackAR0, AgeRichness)
      } else if(year == 100){

        names(SppRich) = paste0(scenario,run)
        StackSR100 = addLayer(StackSR100, SppRich)

        names(AgeRichness) = paste0(scenario,run)
        StackAR100 = addLayer(StackAR100, AgeRichness)
      }
    }
  }
}
```

```

}

Biodiv = rbind(Biodiv, c(year, scenario, SppRich_mean, AgeRichness_mean, run))
}
}
}

colnames(Biodiv)=Biodiv[1,] %>% unlist %>% as.character
Biodiv=Biodiv[-1,] %>% as.data.frame()

j=c(1,3,4)

Biodiv[ , j] = apply(Biodiv[ , j], 2,
  function(x) as.numeric(as.character(x)))

```

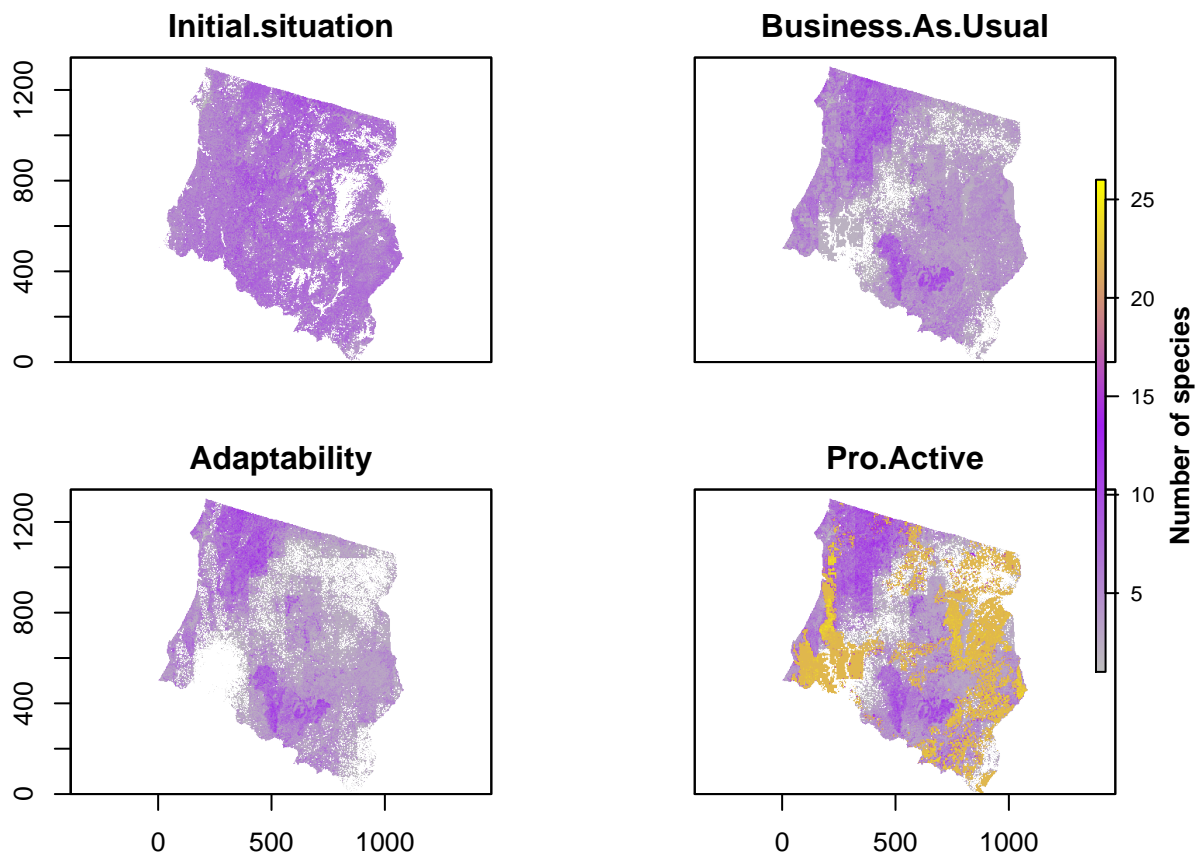


Figure 24: Species richness after 100 years by scenario

Species richness before and after the simulation shows a loss for the BAU scenario. Zones of maximal and minimal richness are not situated at the same place after 100 years. The adaptability scenario shows the same pattern that the BAU but with reduced richness. The important number of species planted in the Pro-active scenario (11) explain important zones of richness limited to the planted areas. Except for these plantations, the pattern of the final species richness seems on a stage intermediate between BAU and Adaptability.

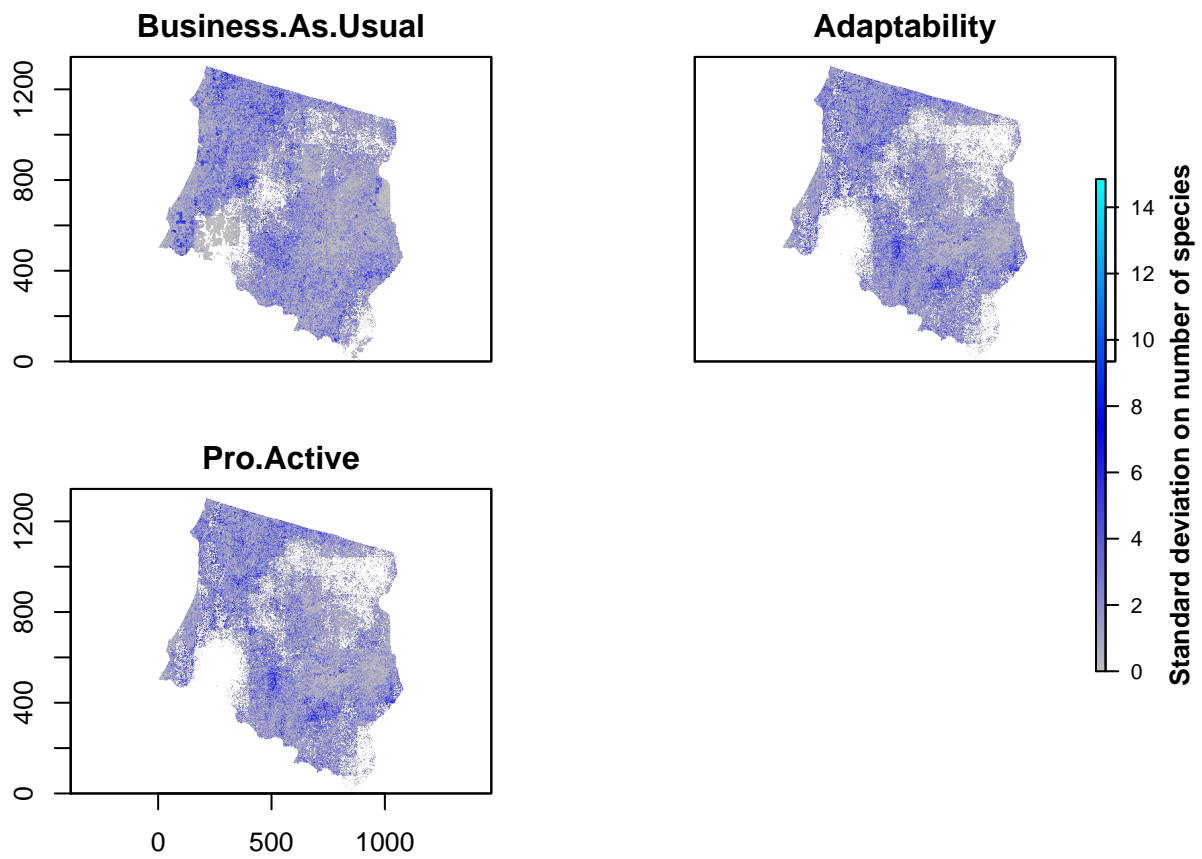


Figure 25: Standard deviation on species richness

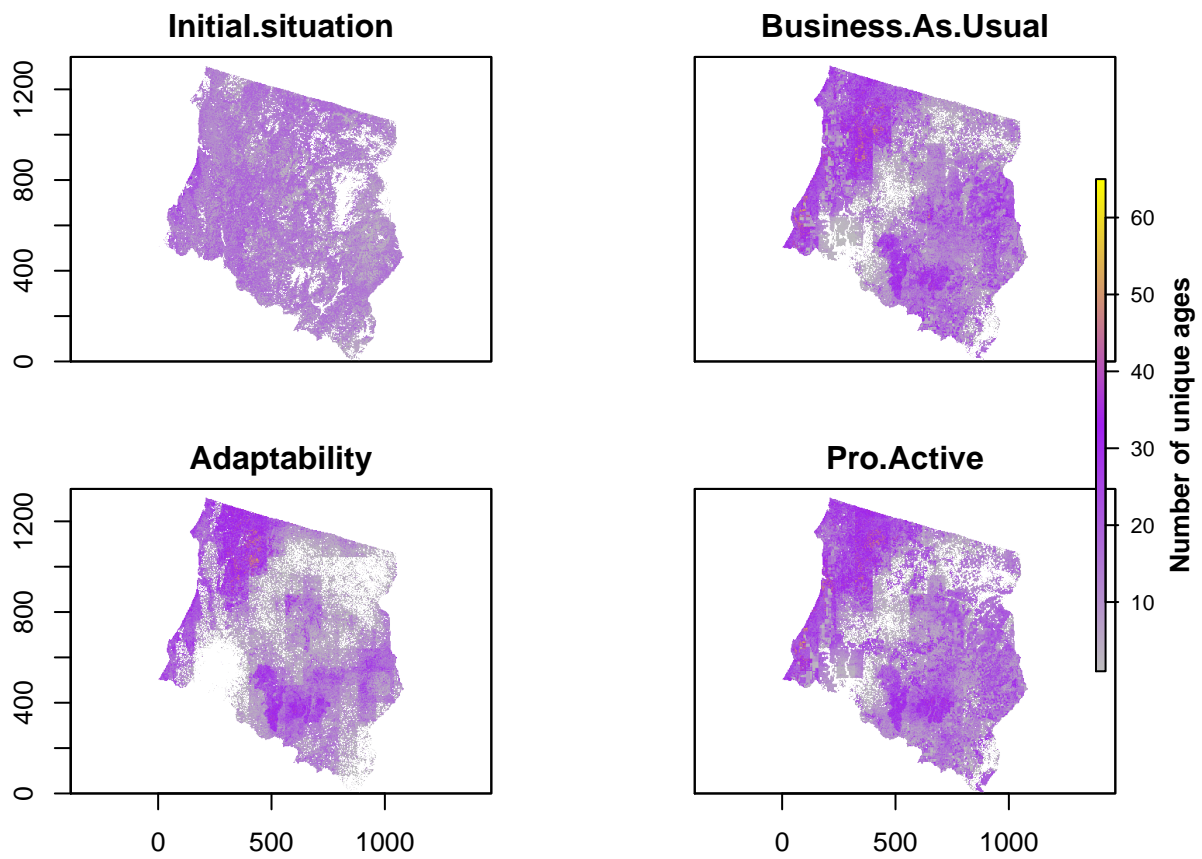


Figure 26: Age richness after 100 years by scenario

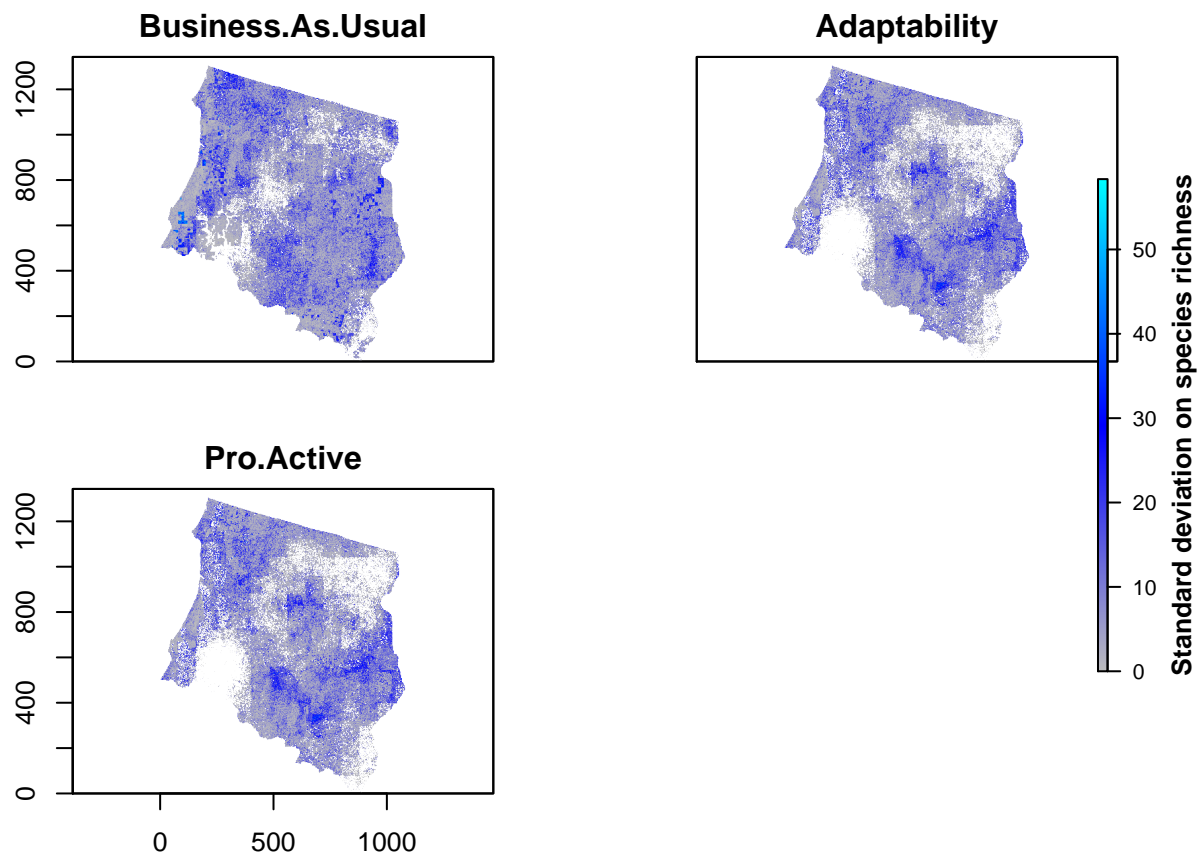
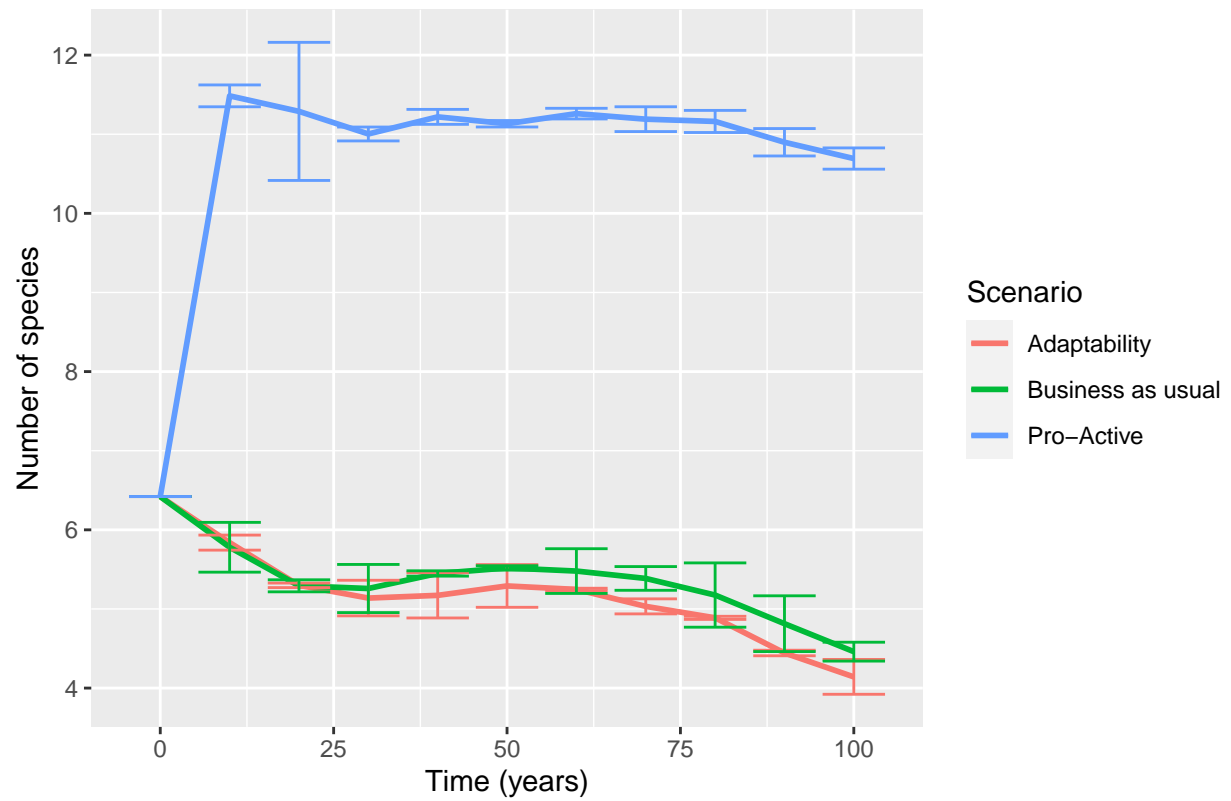
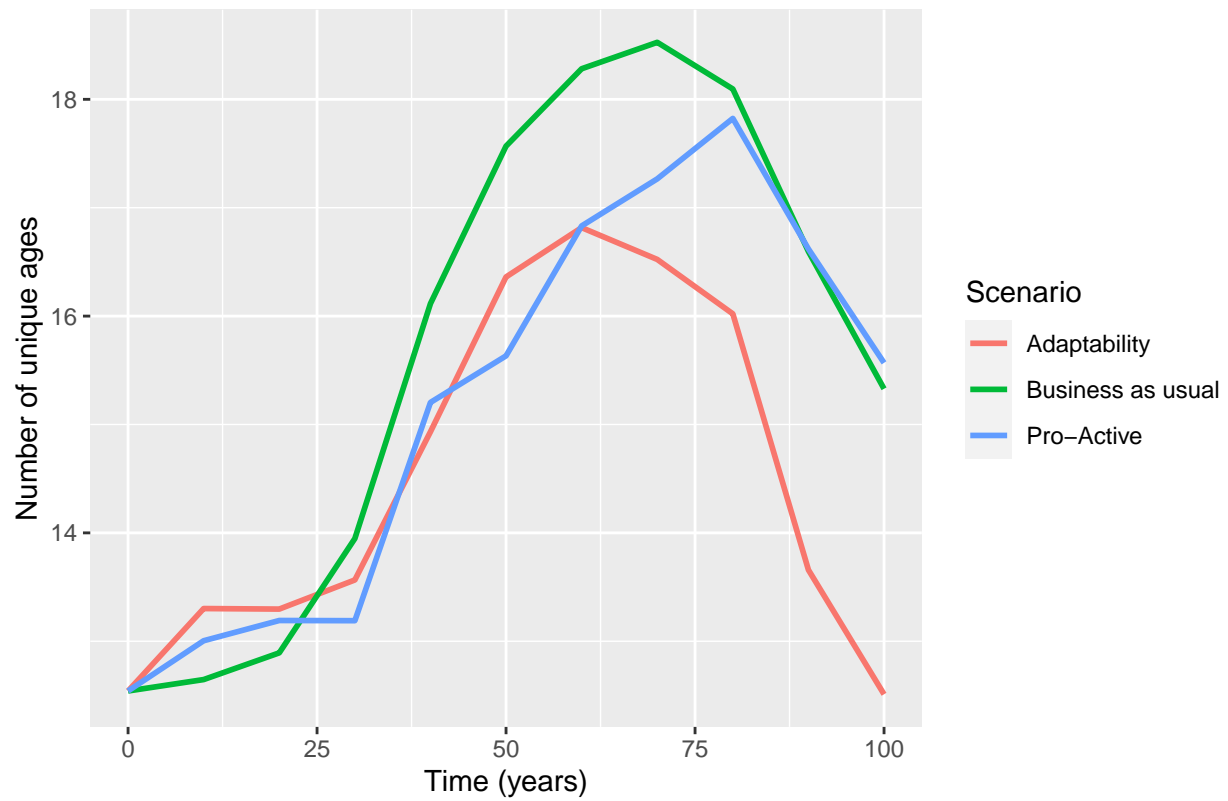


Figure 27: Standard deviation on age richnes

Evolution of number of species per cell on different scenarios



Evolution of age richness per cell on different scenarios



The average number of species by cell have the same general behavior in all the scenarios, with a decrease after the 60th year. For increasing species richness, the Pro-active scenario

Evolution of age richness per cell on different scenarios

