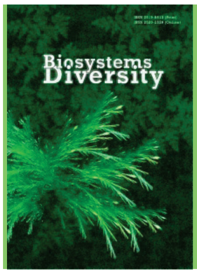

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Impact of climate change on forest resources: Case of *Quercus rotundifolia*, *Tetraclinis articulata*, *Juniperus phoenicea*, *J. oxycedrus*, *J. thurifera* and *Pinus halepensis*

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Forest resources in the Ourika watershed are subject to several anthropogenic and climatic degradation factors. As for the human factor, this degradation of forest resources is explained by the bad practices exercised by the local population expressed by the cutting of live wood, carbonization, and overgrazing. In terms of the climatic factor, the decrease in the amount of rainfall and the increase in temperature contribute to the exacerbation of the degradation of these resources. In order to better understand the evolution of plant cover in a changing climate context, this study highlights an assessment of the impact of climate change on forest dynamics based on a process-based model at the forest landscape scale which makes it possible to simulate the changes according to growth, succession, disturbances (fire, wind, insects, etc), forest management, and land use change. This analysis is based on the use of the LANDIS-II model and the PnET-succession extension. Projections of the dynamics of forest communities are made using climate projections from the Japanese global circulation model adopted by Morocco (model for interdisciplinary research on climate – earth system models) and this by adopting the two climate scenarios , representative concentration pathways 4.5 and 8.5. The results obtained highlight the spatial distribution of the ecosystems studied after 100 years with a quantitative evaluation of the total average biomass of these resources as a function of climatic disturbances. In general, the estimated total biomass will decline over the coming years under the joint effect of the climate change and the aging of forest stands, while on the other hand, the distribution of potential areas for species settlement remains independent of the effect of these climate changes.

Keywords: climate change; forest resources; LANDIS-II; PnET-succession; modeling; Morocco.

Introduction

Forests are essential ecosystems for life on earth, thanks to their role in regulating the climate, protecting the soil, preserving water, and conserving biodiversity. They provide a multitude of ecosystem services, fundamental elements of the global economy, and human well-being (Haines-Young & Potschin, 2010). Nevertheless, forest resources and natural ecosystems are confronted with several disturbances of various origins and of very varying degrees of intensity. Among these disturbances is climate change which will have serious consequences, even considering the most optimistic scenario (Masson-Delmotte et al., 2018). Among the most significant impacts of climate change are increased surface temperature, reduced rainfall in some regions (Stocker et al., 2013), reduced water quantity and quality (Flato et al., 2013; Trenberth et al., 2015), and consequently land degradation and the regression of natural resources in general and forest resources in particular (Masson-Delmotte et al., 2018). Various studies have identified the Mediterranean region as a global 'hot spot' for climate change, where precipitation is expected to decrease and temperatures to increase (Lionello et al., 2018). This region is one of those most exposed to water stress, because of the high variability of water resources between years, space and time and the decrease in water supply expected in the coming decades (Ulbrich et al., 2013). Problems with water quantity and quality can have disastrous consequences, not just for wildlife and plants but for the economy, health and well-being of the human community (Masson-Delmotte et al., 2018). In this perspective, understanding and identifying the range of potential negative impacts of global change on forest ecosystems is the keystone to better managing them in the future and preserving their major contribution to human well-being (Lindner et al., 2014; Mina et al., 2021).

In Morocco, the Ourika watershed belongs to the marginalized mountainous areas, under-equipped, where the environmental problems are linked, on the one hand, to the aggressiveness of the natural conditions and on the other hand, to the disruption of the production systems, consumption, and management of space and resources. Indeed, the forest resources in this basin have experienced a clear decline in the area. Thus, the geographical extent of the Ourika Forest has decreased by 42% from 14,029 ha in 1987 to 8,098 ha in 2019, i.e. the share of forest compared to the overall area of the watershed has fallen from 24% to 14% over the past three decades. On the other hand, bare land (land devoid of any human intervention), rangelands, and arboriculture are increasingly invading the land surface of the basin (Elmalki et al., 2020). This degradation is due to the combined effect of human action exerted on natural resources in order to respond to the growing needs of the local population in the absence of permanent and appropriate economic activity and climate action marked by a reduction in rainfall and rising temperatures (Choukrani et al., 2018; Elmalki et al., 2020). With the constancy of anthropogenic pressure, it, therefore, becomes important to understand the part of the dynamics associated with climate changes in order to better direct the action of the managers in favour of the preservation of natural capital. In this sense, the use of models makes it possible to make projections to enlighten the decision-maker.

In recent years, the importance of using computer models in forestry research has also gained great importance (Gustafson et al., 2017; Shifley et al., 2017). While empirical research is of crucial importance for understanding processes, simulation models are now recognized as useful tools for assessing knowledge of ecosystem functioning as well as essential allies for predicting future changes (Seidl, 2017). LANDIS-II (Scheller et al., 2007) is one of the models for simulating forest landscapes at a wide range of spatial and temporal scales (De Bruijn et al., 2014; Simons-Legaard et al., 2015).

The present study aims to project the dynamics of forest resources in the Ourika watershed over a period of 100 years to better understand their evolution, considering future climate conditions as projected using the General Circulation Models of MIROC-ESM (Japan) for the two climate scenarios RCP 4.5 and RCP 8.5 in order to better reason and prioritize forest resource management efforts.

Material and methods

In the High Atlas of Morocco, the Ourika watershed is located between latitudes 31°00' N and 31°21' N, and longitudes 7°30' W and 7°60' W (Fig. 1), and covers an area of 573.63 km^2. It is bounded to the south by the upper basin of the Oued Souss, to the north by the Haouz Plain, to the east by the Zat watershed, and to the west by the Rheraya watershed (Saidi et al., 2012). It is a sub-basin of the large Tensift watershed which occupies the central-western part of the High Atlas mountain range, covering an area of 20,450 km². The Ourika watershed area has an approximately elongated shape and a compactness index of 1.49 with $K_c = 0.28\ P/\sqrt{S}$, where P is the Perimeter and S the Surface area (Roche, 1963). Its main watercourse, which runs northeast and then northwest after the town of Setti Fadma, crosses a long, steep valley towards which a succession of tributary valleys and ravines converge on both banks (Saidi et al., 2010). The topography of the watershed area is very uneven with sharp variations in altitude. The altitude distribution shows that 63% of the basin's surface is located between 1,500 and 3,000 m and the average altitude is 2,438 m (Elmalki, 2022). On the pedological level, marl, clay, and limestone rocks represent an area of less than 35%, while crystalline rocks (the hard substrate) represent approximately 67% of the area of the basin (Pascon, 1983).

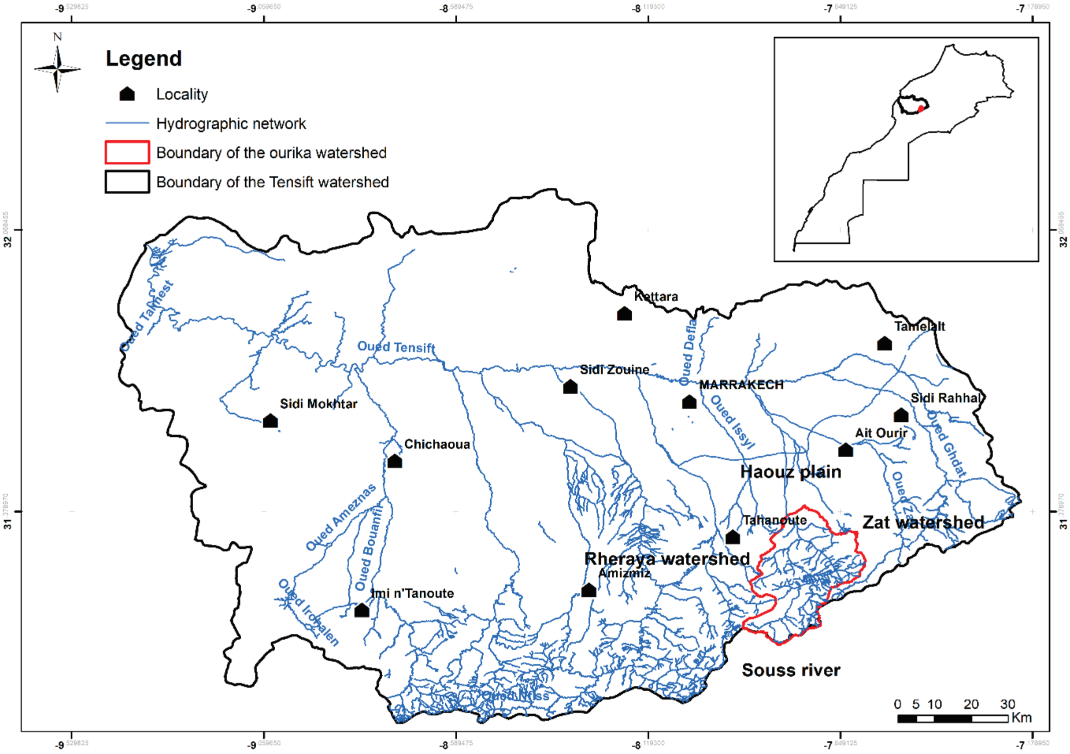

Fig. 1. Geographic location map of the Ourika watershed

Rainfall is a factor that characterises a climate, not only by the annual quantity of water collected, but also by the number of rainy days (rainfall) and their distribution in the year (rainfall regime). Its influence is strongly correlated with the soil water balance and the behaviour of plants. The Ourika watershed records average annual rainfall ranging from 255.5 to 489.1 mm according to an analysis carried out on four meteorological stations of the Tensift Hydraulic Basin Agency, which are well distributed throughout the study area over a series of 21 years on average (1996–2016) (Elmalki, 2022). Also the annual average temperatures according to the same stations mentioned above during this period and according to NASA data vary from 13.26 to 15.96 °C (Elmalki, 2022).

The different vegetation formations of the Ourika watershed are diversified. Depending on the climatic domain, there is vegetation from the oceanic domain, represented by the oleaster (*Olea europaea* var. *oleaster*), the prickly juniper (*Juniperus oxycedrus*), the holm oak (*Quercus rotundifolia*), and the Spanish juniper (*J. thurifera*), and the vegetation of the semi-internal domains, which is made up of the Barbary thuja (*Tetraclinis articulata*), Phoenicean juniper (*J. phoenicea*) and prickly juniper (*J. oxycedrus*) and finally vegetation of the internal domains expressed by the presence of two shrubby species of Papilionaceae (Fabaceae) endemic to this region, *Retama dasycarpa* and *Adenocarpus anagyrifolius*. They are considered as degradation formations of the oak or juniper forest or even of the thuriferous forest (Emberger, 1939). All of these forest formations make up the Ourika Forest, which has been the subject of an integrated development plan allowing for a short and medium term management plan with the aim of sustainable and integrated development of forest resources. The present study uses LANDIS-II to simulate forest resource dynamics at several spatial and temporal scales (Scheller et al., 2007). It provides a large range of events based on a range of extensions that can be optionally activated to simulate different processes as succession, disturbances (fire, wind, herbivores and pests) and management at different complexity levels (e.g. specific species-areas and harvesting regimes, post-harvest planting), the spatial level (i.e. the resolution of the cells) is user-defined, making it very flexible and adaptive to a large variety of simulation experiments (Suárez-Muñoz et al., 2021). In LANDIS-II, the terrain is divided into ecoregions, which are sub-regions sharing similar climatic conditions and soil characteristics. Within each cell, trees are represented as species and age cohorts, thus, the model simulates cohort development with reference to ecoregions, increasing the model's computational efficiency (De Bruijn et al., 2014).

The LANDIS-II version is linked to its new process-based model extension PnET-Succession v.3.4 (De Bruijn et al., 2014; Gustafson et al., 2015) and incorporates the equations of the one-dimensional ecophysiology model PnET-II (Aber & Federer, 1992). The simulation of forest succession in PnET-Succession is more mechanistic than other approaches (Gustafson, 2013), which is an advantage for experiments where new conditions such as climate change are explored. At the start of the simulation, the PnET-succession uses age to calculate the cohort biomass. The cohort biomass is assumed to be homogeneously distributed within the cell and therefore the conditions of shadow are also similar at the cell level (Scheller et al., 2007). The potential rate of net photosynthesis is calculated as a linear function of leaf nitrogen (FolN). The environmental conditions such as temperature, precipitation, photosynthetically active radiation (PAR), CO_2 concentrations, and possibly ozone concentrations are at the origin of the biomass growth (De Bruijn et al., 2014). Mortalities can arise at any time when carbon reserves become limited (non-structural carbon <1%) or when a plant approaches the end of its lifespan (De Bruijn et al., 2014).

PnET-succession needs a generic set of ecoregion- and species-specific parameters. While there are many default values available from the model designers and from previous application studies, most of these parameters require calibration to the biogeographic situation of the landscape of interest and the specific species included in the model simulations (McKenzie et al., 2019; Mina et al., 2021).

The LANDIS-II model requires specific data to ensure optimal operation of its PnET-succession extension. These data are collected from different sources depending on their availability and reliability. Thus, a detailed description of the acquisition procedure of all the products required by LANDIS-II is presented.

The climate data used to run this forestry model were taken from the World Bank's Climate Change Knowledge Portal database for the period 1961–2020 (Climate Change Knowledge Portal). On the same basis, projections are made using the MIROC-ESM model (Japan), for the two commonly adopted climate scenarios, RCP 4.5 and RCP 8.5 (Masson-Delmotte et al., 2018), as well as the reference scenario over the period 2000–2100. The choice of this model is based on climate studies conducted in Morocco by the Food and Agriculture Organization (FAO) in 2015 using the said model and also on the availability of data. The model uses monthly data of five variables: maximum temperature (T_{max}), minimum temperature (T_{min}), precipitation, photosynthetically active radiation (PAR) and CO_2 concentration in the atmosphere.

The initial community map is extracted from the stand type map of the Ourika Forest management study carried out in 2002 (Hceflcd-Ha, 2002), by merging the parameters: composition and development status of the type described. The stand-type map of the Ourika Forest was digitised and processed using appropriate geographic information system software. The information is recorded on different levels (layers) in order to make it easier to manage. The initial map was established on the basis of the restitution of information extracted from aerial photographs according to the photo-interpretation procedure associated with field missions (Hceflcd-Ha, 2002).

The aim is to define for each forest species composing the Ourika Forest massif, certain characteristics describing its behaviour with respect to well-defined ecological and climatic conditions. The identification of these characteristics is a combination of two sources of information, namely the bibliography as the first source (Pausas et al., 2004; Valladares, 2005; Niinemets et al., 2006; Serrada et al., 2008; Kattge et al., 2020; Suárez-Muñoz et al., 2021), local data (www.try-db.org/TryWeb/home.php) and expert opinion as a second source to complete the bibliography.

These are geographical areas with a unique character in terms of soil, climate, geomorphology, geology, water resources, fauna, and flora, the objective of defining these these ecoregions is to reduce the huge variations in the landscape into a collection of homogeneous areas. Since the present study is conducted on a geologically and hydrologically limited watershed, the determination of ecoregions is defined from the intersection of the parameters:

– geomorphological: slopes, elevations, and exposures, extracted from the Digital Elevation Model with 30 m spatial resolution (Gdem-Aster),

– climatic: represented by annual average precipitation and temperature, taken from the WorldClim 2 platform with a spatial resolution of 1 km (Fick & Hijmans, 2017), and

– pedological are obtained from the FAO World Soil Map with a spatial resolution of 1 km (The Harmonized World Soil Database).

These parameters were retained because they condition the distribution of forest species. It should be noted that the spatial resolution of the input data of the Landis-II model was reduced to 30 m according to the requirements of the model and the objectives assigned to the present work, and all the information processing and mapping processes for the different phases of this study are carried out on the ArcGIS and QGIS graphic interfaces. On another note, the duration chosen for the realization of this simulation is spread over 100 years with a step of 10 years from the year 2000 (the date of the realization of the management of the Ourika Forest) in order to better understand the behaviour of the forest species and their reaction according to the biomass and the distribution area.

Results

The results of the process of preparing the data necessary to proceed to the simulation of the effect of climate change on forest resources in the Ourika watershed allowed us, first of all, to establish a map of initial communities from the map of stand types, with the identification of 22 initial communities spread over the whole territory studied, by combining the composition of the stand (pure or mixed) and the state of development of the species (young, adult or old) to subsequently allow the definition of the age classes of the different species of the Ourika Forest (Cohorts) (Fig. 2). It should be noted that community n°8 is missing because of its imperceptible surface. Generally speaking, six forest species make up the map of the initial communities of Ourika, these are the holm oak (*Quercus rotundifolia*) which predominates in terms of surface area, the Barbary thuja (*Tetraclinus articulata*) which comes second, prickly juniper (*Juniperus oxycedrus*), Spanish juniper (*J. thurifera*), Phoenicean juniper (*J. phoencia*) and finally Aleppo pine (*Pinus halepensis*) in the form of reforestation. All of these species are found in a pure state and in mixtures (Table 1).

Also, a map of the ecoregions was produced by intersecting all the geomorphological, climatic, and pedological parameters of the study area. Figure 3 shows the spatial distribution of the 14 eco-regions resulting from this process of superimposing the biophysical parameters characterizing the Ourika watershed.

Finally, Table 1 summarises some of the parameters of the species that make up the Ourika watershed forest massif. These values have been extracted from the bibliography, from the database on plant characteristics and from the opinions of expert researchers and managers.

The application of the Landis II model to the different communities using: current climate conditions (as a reference) and climate projections for 2100 from the Japanese global circulation model (Miroc-ESM) according to the two scenarios: optimistic, RCP 4.5 (which is based on the assumption of stabilization of greenhouse gas emissions in 2050) and pessimistic, RCP 8.5 (which considers that greenhouse gas emissions will continue to trend upwards until 2100), makes it possible to project the distribution and composition of the massif to the year 2100 while taking into account the two-time units: the decade and the month.

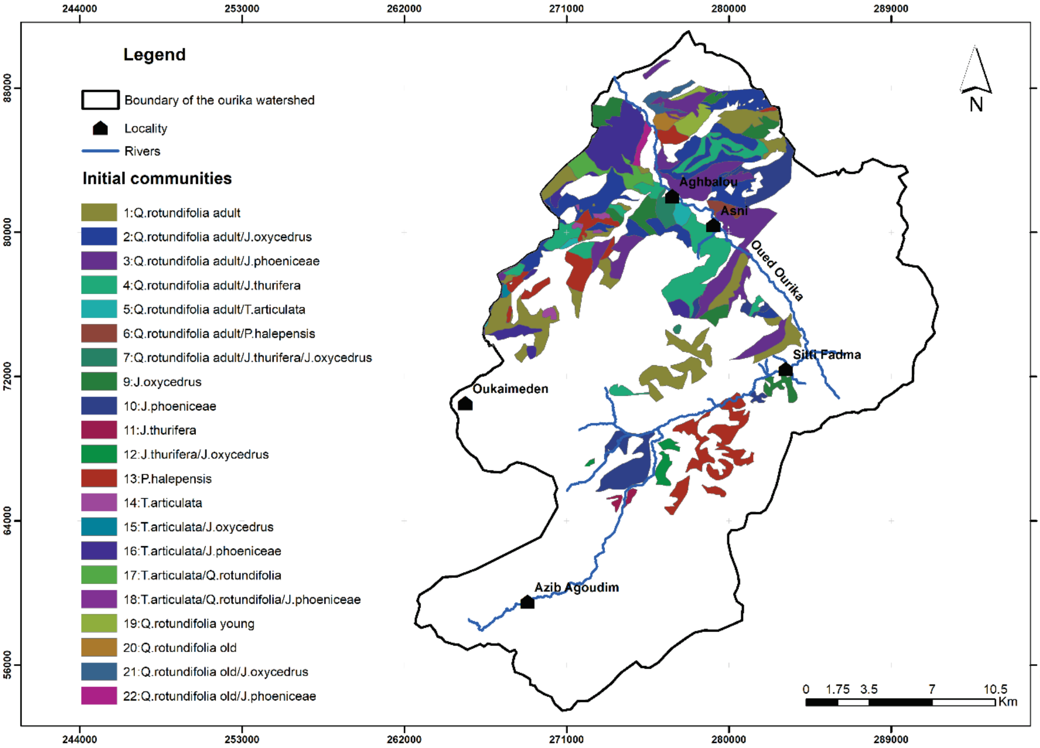

Fig. 2. Map of the initial communities of the Ourika watershed

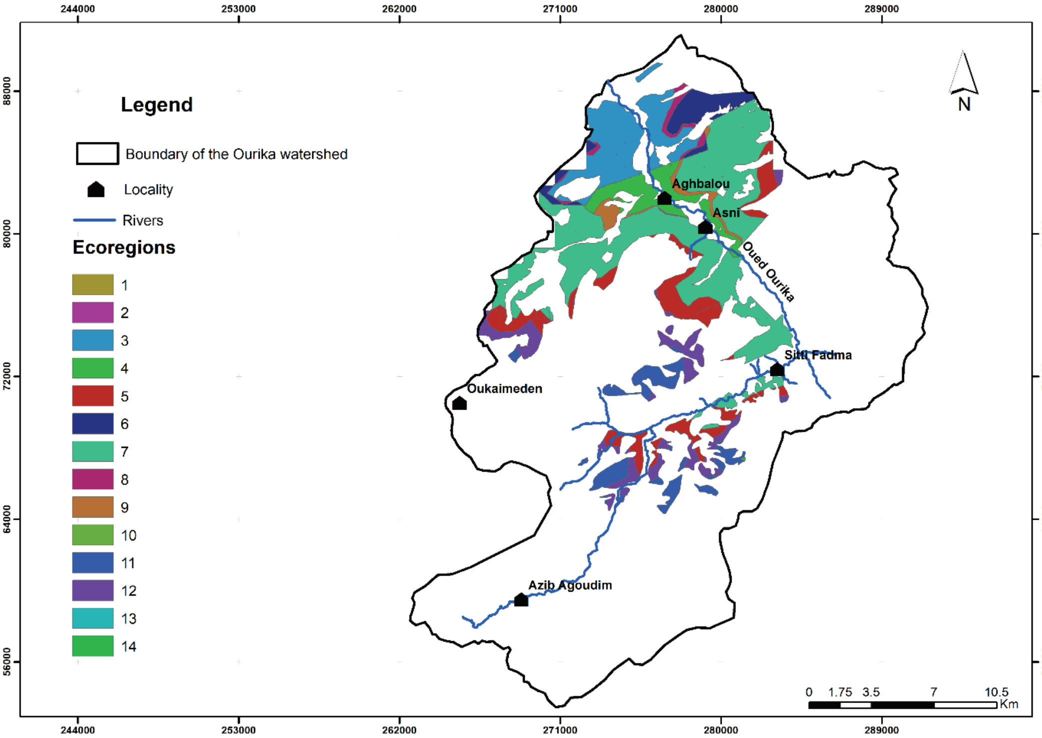

Fig. 3. Map of the ecoregions of the Ourika watershed

Table 1
Some forest species parameters for LANDIS-II and PnET-Succession

Species	Code	Longevity, year	Sexual maturity, year	Helio-philiacy, /5	Fire tolerance, /5	Effective dispersion distance, m	Maximum dispersion distance, m	Probability of vegetation	Minimum age to reject, year	Maximum age to reject, year
Quercus rotundifolia	querrotu	600	15	4	1	300	700	1.0	10	600
Tetraclinis articulata	tetrarti	400	15	5	1	2	30	0.6	40	280
Juniperus phoenicea	juniphoe	600	17	4	3	2	30	0.2	10	600
J. oxycedrus	junioxyc	600	17	5	3	2	30	0.2	10	600
J. thurifera	junithur	600	17	5	3	2	30	0.2	10	600
Pinus halepensis	pinuhale	150	20	4	1	100	1000	0.0	10	20

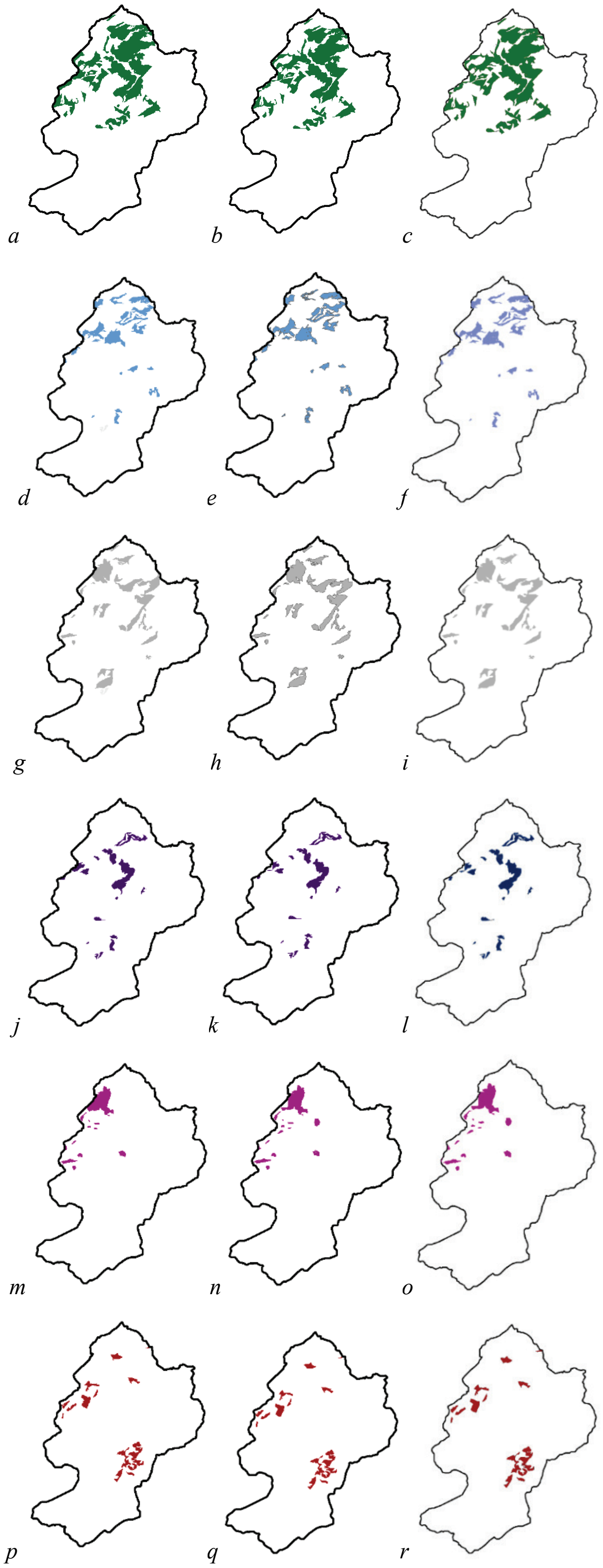

Fig. 4. Spatial distribution of forest species: *Quercus rotundifolia* (*a*), *Juniperus oxycedrus* (*d*), *J. phoenicea* (*g*), *J. thurifera* (*j*), *Tetraclinis articulata* (*m*) and *Pinus halepensis* (*p*), in the Ourika watershed between 2000 and 2100, according to the reference (*a*, *d*, *g*, *j*, *m* and *p*), optimistic RCP 4.5 (*b*, *e*, *h*, *k*, *n* and *q*) and pessimistic RCP 8.5 (*c*, *f*, *i*, *l*, *o* and *r*) scenarios

The cartography presented in Figure 4 makes it possible to visualize the spatial and temporal distribution of the main species making up the Ourika Forest massif over the next 100 years from the reference year 2000. This spatiotemporal configuration offers the possibility to distinguish in a significant way the areas where the species will have more probability and chance to settle naturally according to the climatic conditions expressed by the two scenarios of the 2018 IPCC report.

Also, Table 2 expresses this spatial distribution of each forest species as a function of area (ha) for the two study dates and according to the two climate scenarios considered. Likewise, it confirms the results obtained from the mapping of the distribution areas of the species through the areas that remain the same.

Table 2
Area of each forest species in 2000 and 2100 according to the two climatic scenarios (RCP 4.5 and 8.5)

Species	Area in ha (2000)	Area in ha (2100)	
		RCP 4.5	RCP 8.5
Juniperus oxycedrus	3 239	3 239	3 244
J. phoenicea	4 285	4 285	4 285
J. thurifera	2 001	2 001	2 001
Pinus halepensis	1 615	1 615	1 615
Quercus rotundifolia	9 006	9 006	9 005
Tetraclinis articulata	1 555	1 555	1 559

Furthermore, the use of the LANDIS-II model and especially its PnET-Succession extension has made it possible to trace the evolution of the average biomass of forest species over the next ten decades, with the aim of preparing for the constraints that will be posed by climatic disturbance, for an adequate understanding of the behaviour of forest resources in order to better act in time and space. Figure 5 illustrates this temporal evolution of the average biomass of each forest species according to the two recommended climate scenarios (pessimistic and optimistic) compared to the reference scenario and the Japanese climate model used (MIROC-ESM).

Discussion

The analysis of the results of the spatial distribution of forest ecosystems in the Ourika watershed clearly shows great independence in the distribution of the vegetation cover in relation to the predicted climate changes. This independence is explained by the conservation of each species of its initial area of distribution and settlement after 100 years of evolution. Indeed, this distribution seems to be consistent with the ecology of all the species studied. Thus, these results confirm the climatic range of the species as well as indicated by Emberger (1939). On the other hand, this state of affairs can be explained by the absence of seed transport factors allowing a wide distribution of stands, this observation is well illustrated by Table 2 which testifies to a maximum dispersal distance that does not exceed 30 m for Phoenicean juniper, Spanish juniper, prickly juniper, and Barbary thuja. Even for the other species, this distance remains minimal and is limited to 1000 m for the Aleppo pine and 700 m for the holm oak. On another note, this simulation was carried out without taking into account disturbances related to forest management and the health status of forest resources in the study area, and other disturbance factors.

In addition, the results found are also influenced by the probability of vegetation for these species, which is very low (Phoenicean juniper, Spanish juniper, and prickly juniper and Barbary thuja). This calls into question the question of the rehabilitation of these forest ecosystems. Indeed, several authors confirm that with the current rate of degradation, the populations of these species are threatened with extinction (Gauquelin et al., 2012). Hence the need to carry out direct interventions of a silvo-pastoral nature by providing these stands with technical conditions favourable to natural regeneration and to protect them against human pressure (intensive grazing, excessive illegal harvesting of fire etc.).

The analysis of the results relating to the evolution of the simulated average total biomass (wood, roots, and foliage) of the various species of the Ourika Forest, shows a tendency for the increase in the biomass during the first twenty years (2000–2020), then a gradual decline over the following years (2020–2100). This trend differs between species and scenarios. Indeed, all the species (with the exception of Barbary thuja) show a slow decrease in biomass for the RCP 4.5 scenario compared to a rapid decrease for the RCP 8.5 scenario. On the other hand, the evolution (increase/decline) of thuja is fast for the RCP 8.5 scenario compared to a slow evolution for the RCP 4.5 scenario. Also, the range of simulated average total biomass production varies from a maximum of 38.5 t/ha (RCP 4.5) for Phoenicean juniper to a minimum of 3.7 t/ha (RCP 8.5) for thuja. For the other species, the maximum production is as follows: holm oak is 32.2 t/ha (RCP 4.5), Spanish juniper is 16.4 t/ha (RCP 4.5), prickly juniper is 27.5 t/ha (RCP 8.5) and the Aleppo pine is 19.9 t/ha (RCP 4.5), these biomass values remain low and very low as they testify to the degraded state of the forest stands. Similarly, these results are consistent with those found in other studies (Nduwayo et al., 2017). The two models (optimistic and pessimistic) present a more accelerated decreasing rhythm compared to the reference scenario, also, the reference scenario of the holm oak and the Aleppo pine keeps an increasing trend following their stage of young and adult development. This general architecture of the evolution of stand biomass compared to the reference scenario is explained by the combined effect of climate change and the state of aging of the Ourika Forest in view of an almost total absence of the natural regeneration of most forest species (Phoenicean juniper, prickly juniper, Spanish juniper, and Barbary thuja) (Ouhammou et al., 2013).

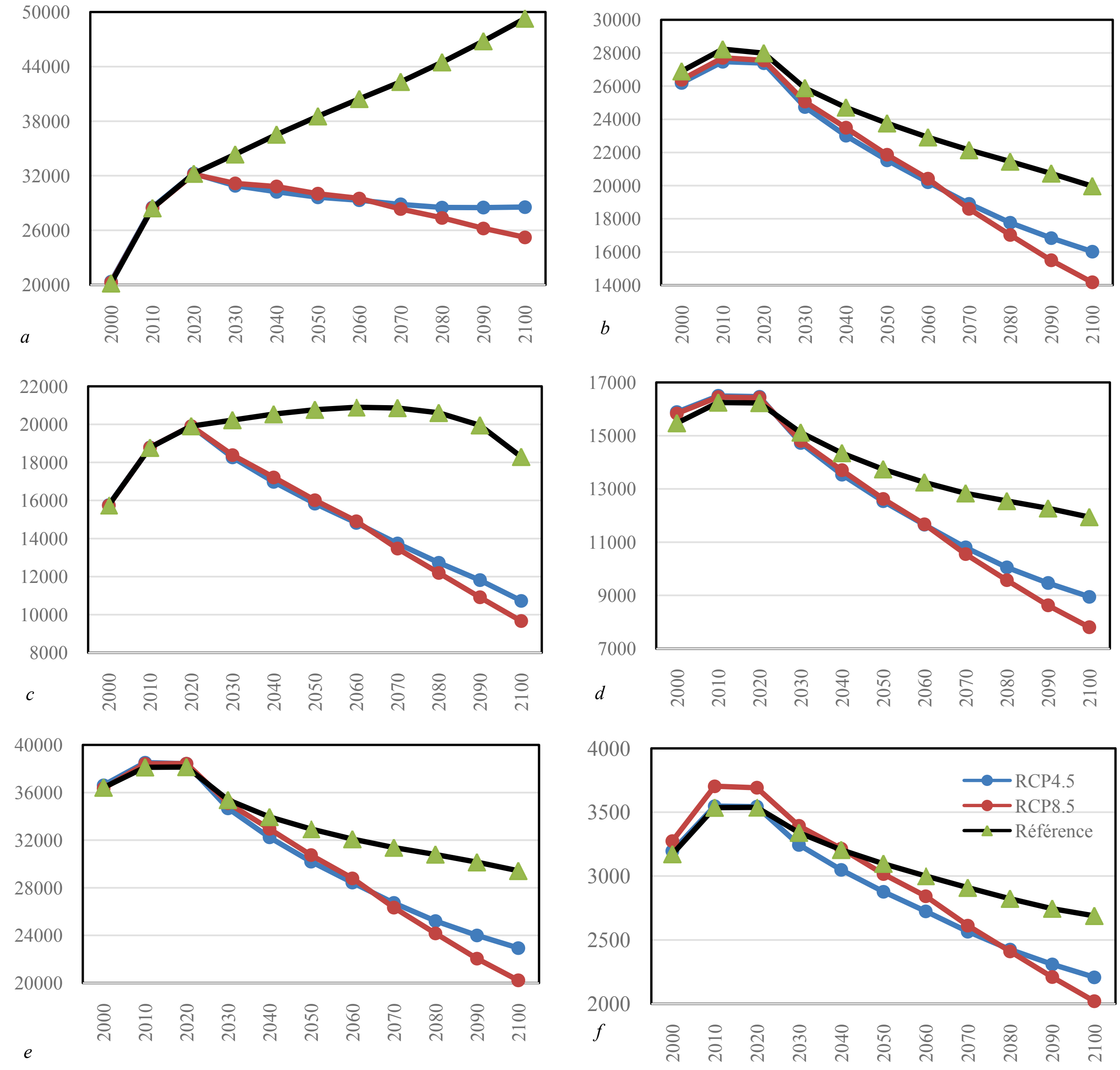

Fig. 5. Evolution of the average total biomass (kg/ha) of the main forest species of the Ourika watershed: *Quercus rotundifolia* (*a*), *Juniperus oxycedrus* (*b*), *Pinus halepensis* (*c*), *J. thurifera* (*d*), *J. phoenicea* (*e*) and *Tetraclinis articulata* (*f*), for the two climate scenarios (RCP 4.5 and 8.5) compared to the reference scenario: on the x-axis – years; on the y-axis – average total biomass (kg/ha)

Hence the need to think seriously about species that can replace them with a higher ability to regenerate, while ensuring soil protection and wood and fodder production. The effect of climate change on biomass production is significant because of the large difference between the two scenarios (optimistic and pessimistic) and the reference scenario. These results confirm those found by Lahssini et al. (2017), who rank climate change as the sixth priority for action (out of a total of 7 levels) after human health, water, biodiversity, agriculture/fisheries, disaster exposure. However, thuja shows a more resilient and favourable character to more severe climatic conditions, so it is imperatively recommended in areas where climate change is an issue with holm oak, while respecting the pedological vocation of this species.

Conclusion

In view of the problem of climate change and its accentuated impact on natural resources in general and forest resources in particular, the adoption of new computer tools more adapted to the current and future climatic context in terms of analysis, evaluation and simulation remains essential. The latter allows a better understanding of the phenomenon in question and also the factors acting in favour or against the said phenomenon, in order to ensure effective, efficient and resilient planning of these resources in space and time.

Among these new tools is Landis-II, a computer model based on a set of extensions including the PnET-succession extension. Indeed, this model can provide more justified answers to certain questions posed by managers and scientists, especially those related to the evolution of biomass and the current state of forest species, and the potential geographical areas suitable for their installation in the future.

Moreover, the results obtained in the framework of the present study show that, with regard to the future distribution of forest cover in the Ourika watershed, climate change does not have a considerable effect on the potential distribution areas of forest ecosystems. Nevertheless, the estimated total biomass is influenced by the effect of climate change and the aging of stands. This calls on managers and decision-makers to focus on the technical issue of rehabilitation of these ecosystems from a climate change perspective, with the integration of the human aspect in order to implement a territorial socio-economic development strategy guaranteeing income-generating activities and alleviating the pressure on forest resources.

As for the simulated average total biomass, all the species studied show a trend towards an increase during the first twenty years (2000–2020), followed by a gradual decrease over the coming years (2020–2100). This aspect remains the same for the two recommended climate scenarios (RCP 4. 5 and 8.5) with a slight difference in terms of the rate of change, which is slower in favour of the optimistic scenario compared to a faster rate for the pessimistic scenario (with the exception of Barbary thuja, which shows the opposite behaviour in terms of change). However, the amount of biomass differs between species and scenarios.

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