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Optimal rotation age of *Populus deltoides* considering economic value of timber harvesting and carbon sequestration

Optimale Umtriebszeit von *Populus deltoides* hinsichtlich des wirtschaftlichen Wertes von Holznutzung und Kohlenstoffspeicherung

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Schlüsselbegriffe: *Optimale Umtriebszeit, Plantage, Kapitalwert, Kohlenstoffspeicherung, Bodenwert*

Abstract

The aim of this research is to determine the optimal rotation age of *Populus deltoides* plantations regarding to the timber and carbon sequestration values in the north of Iran. Two plantation types with a tree density of 3 by 3 m and of 3 by 4 m were considered in Choobar forest, northern Iran. Net present value (NPV) of timber and carbon were used for determining the optimal rotation age. Data on volume increment, carbon content, revenue, timber and carbon prices were collected to estimate NPV. In this study, we considered the effects of different plantation cost, land value and discount rates on the optimal rotation ages. Our results indicated, if economic value of timber is considered, optimal rotation ages were 10 and 8 years for 3 by

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3 m and 3 by 4 m density, respectively. Optimal rotation ages considering carbon sequestration, in addition to timber value, increased to 14 and 11 years for the same two densities, respectively. Thus, integrating carbon sequestration value with timber economic value increased the optimal rotation ages and in turn change the optimal forest management. Sensitivity analysis indicate that optimal rotation ages increased with increasing plantation cost and decreased with increasing interest rate, while our results suggested that the optimal rotation age is not sensitive to the land value. Our results are important for land managers and carbon projects to optimize the used forest management practices.

Zusammenfassung

Ziel dieser Studie ist die Ermittlung der optimalen Umtriebszeit von *Populus deltoides*-Plantagen hinsichtlich Holzproduktion und Kohlenstoffspeicherung im Norden Irans. Zwei unterschiedliche Bestandesdichten von 3 mal 3 m und 3 mal 4 m wurden im Choobar Wald. Iran, untersucht. Wir haben den Kapitalwert (NPV) verwendet um die optimale Umtriebszeit zu bestimmen. Hierfür wurden Daten zu Volumszuwachs, Kohlenstoffgehalt, Gewinn, Holzpreis und Kohlenstoffpreis gesammelt. In diese Studie berücksichtigen wir die Effekte der Bestandesbegründunskosten, des Bodenwertes und der Zinsrate auf die optimale Umtriebszeit. Berücksichtigt man nur die Holzproduktion ergibt sich eine optimale Umtriebszeit von 10 bzw. 8 Jahren jeweils für die zwei Bestandesdichten von 3 mal 3 m und 3 mal 4 m. Wenn man zusätzlich noch die Kohlenstoffspeicherung berücksichtigt, erhöht sich die optimale Umtriebszeit auf 14 bzw. 11 Jahren für die zwei Bestandesdichten. Somit bewirkt eine Integration des Wertes der Kohlenstoffspeicherung eine Verlängerung der optimalen Umtriebszeit und damit eine Veränderung des Waldbausystems. Die Ergebnisse einer Sensitivitätsanalyse zeigen, dass die optimale Umtriebszeit mit steigenden Bestandesbegündungskosten positiv und mit der Zinsrate negativ korreliert, während die optimale Umtriebszeit relative unempfindlich gegenüber dem Bodenwert. Unsere Ergebnisse sind wichtig für Waldmanager/-innen und Kohlenstoffprojekte in der Optimierung der aktuellen Bewirtschaftung.

1. Introduction

Before human-caused carbon dioxide emissions began, the natural processes that make up the global carbon cycle maintained a dynamic equilibrium between the uptake of carbon dioxide and its release back to the atmosphere. Human activities, especially the burning of fossil fuels such as coal, oil, and gas have caused a substantial increase in the concentration of carbon dioxide in the atmosphere (Sundquist et al. 2008). Therefore, climate change became a global issue of great significance and has been the focus of considerable international attention.

Many international and national agreements and policies, such as the Kyoto Protocol, the Paris Agreement, and the EU climate policy emphasize the importance of carbon stabilization in the atmosphere (Gren and Zeleke, 2016). The Kyoto Protocol is the first step towards achieving the objectives of the United Nations Framework Convention on Climate Change and aims among others to promote 'the protection and enhancement of carbon sinks and reservoirs' (Robertson and Loza-Babuena, 2004). Forests, as the largest natural terrestrial carbon sink, play an essential role in the global carbon cycle (Zhou, 2015; Yousefpour et al., 2018).

Governments attempting to reduce or control carbon emission growth carry out different pricing approaches for carbon. Carbon pricing mechanisms are an effective way to shift external costs towards polluters (Boussemarta et al., 2017).

The optimal rotation age (time between two harvestings) maximizes the profit in even-aged forest management. Determining optimal rotation ages are one of the most important management decisions in multiple-use forest management. Faustmann (1849) developed the first correct formulation of the profit of even-aged stand management. The importance of the optimal forest rotation age for forest management is underlined by its effects on both economic and environmental benefits, which has two main reasons. First, rotation age affects the economic and ecological benefits directly. Therefore, it is important to choose the right rotation age in order to achieve the highest possible benefits, if the landowner's objective is to maximize financial return. Second, defining the optimal forest rotation age is needed to plan other forest management measures, like forest tending or thinning. If carbon sequestration has a monetary value, land owner would manage their forests for both timber and carbon, which may change the optimal rotation age (Zhou and Gao, 2016).

Given the in general long forest rotation periods, most of the previous studies on carbon sequestration considered time horizons in the range of 50–100 years. In the future, however, climate change will likely affect forest dynamics and processes such as reproduction, growth, and mortality of trees and in turn change the forest growth (Goetz et al., 2013).

Populus deltoides plantations in the north of Iran were considered in this study. These plantations are a very efficient system for wood supply to the pulp industry. Iran became a member of International Poplar Commission (IPC) in 1953. Between 1965 and 1970 poplar clones like *Populus deltoides* and *Populus euramericana* were imported and since then used by industry to help fulfill the domestic wood demand in Iran. After planting these poplar clones in research stations, their adaptation potential to climate and environment were investigated. Today poplar and willow plantations cover about 220,000 ha out of an area of 520,000 ha that is suitable for plantation in Iran. About 30 percent of these plantations are located in the north of Iran along the coastal plain of the Caspian Sea, while the remainder extend to the arid and semi-arid regions (National Poplar Commission of Iran, 2015). According to the last statistics the consumption of poplar timber for production of plywood, particleboard and pulp in Iran exceeded 1.66 Million cubic meters in year 2012 (Islamic Republic of Iran Customs Administration, 2012). On an area of 120,000 ha in Iran the clone *Populus deltoides* is planted (Hajjarian, 2013). The even-aged coppice silvicultural system is used to manage these plantations. This is to our knowledge the first study to determine the optimal rotation age of poplar considering the NPV of timber and carbon sequestration in Iran.

Van Kooten et al. (1995), Diaz-Balteiro and Rodriguez (2006), Kula and Gunalary (2012) and Yousefpour et al. (2018) considered the pricing of forest carbon. They found that consideration of carbon benefits extends the optimal rotation significantly, increasing the amount of sequestration of atmospheric carbon. Robertson et al. (2004) analyzed the international carbon credit value and rate of interest for Pinus radiata afforestation projects in New Zealand. Ekholm (2016) investigated that starting from bare land, the initial carbon price and its growth rate both increase the length of the first rotation. The higher growth rate of carbon price can lead to shorter rotations. Goetz et al. (2013) integrated biogeochemical process and economic models to improve the forest management modeling of adaptive measures to climate change and determined the optimal design of carbon mitigation policies at the stand level. Mohammadi Limaei et al. (2013) determined the optimal rotation period of poplar plantations maximizing the NPV of timber in the north of Iran. Results indicated that the optimal rotation age will be varied between 8 and 25 years in different plantation densities and interest rates. Zubizarreta-Gerendiain et al. (2016) investigated the several management policy on carbon balance, they maximized with even-flow, results show that postponing the thinning of young stands and using thinning from above improved carbon balance and NPV. Richards and Stokes (2004) reviewed the carbon sequestration cost studies that have evaluated the economics of the forestry option. The importance of forest plantation for climate change mitigation have been presented in several studies such as Lutz et al. (2013) used growth parameter values as input to the economic model and NPV to evaluate the responses of timber harvest and carbon sequestration to increasing temperature in Russian forest.

The aim of this study is to explore the optimal rotation age of *Populus deltoides* plantations considering the effects of plantation cost, discount rates and land value on optimum rotation ages.

Material and Method

Study area

Two districts (No. 1 and 9) with 36 years old plantations of *Populus deltoides* located in Choobar at Guilan Province, in the north of Iran were used in this study (Fig. 1). This region has a humid climate with a mean annual temperature of 17.0°C and an annual precipitation of 1411 mm. Soils are predominantly brown with pH ranging from 5.8 to 6.7

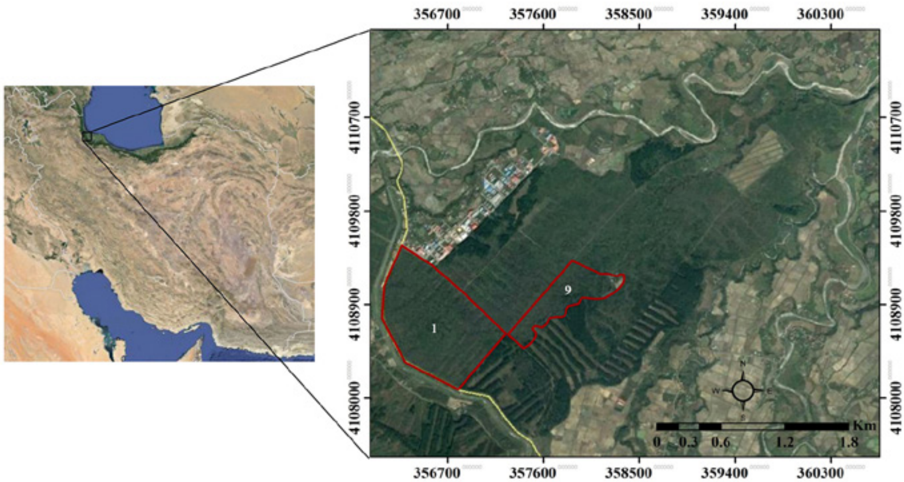


Figure 1: Study area located in North Iran near the Caspian Sea. The right plot shows the location of the two used plantations

Abbildung 1: Untersuchungsregion im Norden Irans nahe des Kaspischen Meeres. Die rechte Abbildung zeigt die Lage der zwei Plantagen.]

Methods

A single plot with an area of 1 ha was sampled in each district (Arora et al., 2014; Mohammadi et al., 2017) after study of the plantation planning prepared by Department of Natural Resources and Watershed Management. The location of the plots were determined randomly, since the plantations were homogenous. For all trees in each plot both diameter at breast height (dbh) and tree height were measured. In total, 30 trees were destructively sampled with regular distribution in diameter classes (Wang, 2006; Segura et al., 2006). The felled trees were separated into two biomass compartments, stem and branches with diameter larger 10 cm. For estimating stem volume and stand increment, discs were taken from different heights of each tree. Stems were cut at a height of 0.3 m above ground. Stems were then cut into 2.3 m sections. At the end of each stem section, a 8 cm thick disc was cut and taken to the laboratory for analysis. The surface of each disc was smooth sanded to reveal the annual growth rings. The tree rings were then measured to estimate the annual increment of the trees (Metsaranta and Bhatti, 2016).

Tree volume was determined based the tree diameter and length. Each stem was subdivided into sections with known length (l) and cross-section (g) both at the lower end (g_l) and the upper end (g_u). Smalian's formula was used for calculation log volume (Zobeiry, 1994):

$$V = \frac{g_l + g_u}{2} l \qquad (1)$$

Where, V is the volume of logs (m^3).

After adding volume of logs per tree, stand volume stock was calculated by multiplying volume of each age classes by number of trees per hectare.

From the sampled discs we cut cube-shaped sub-samples of 4×4×4 cm, weighted them, oven-dried at 100 °C to constant mass and then determined the dry mass with an electronic balance (Henry et al., 2010). The volume and the dry mass measurements were used to calculate the wood density as below:

$$D_C = \frac{W_0}{V_w} \qquad (2)$$

Where, D_C is wood basic density (gr/cm³), W_0 is dry mass of wood (gr) and V_w is the wet volume (cm³).

The percentage of organic carbon of 30 stem and 30 branch samples were determined by combustion in an electric oven (Arora et al., 2014). By multiplying the carbon percentage with biomass (i.e., volume multiplied with wood density), this study considers the carbon stored in live stem and branches biomass. By combining growth rates with wood density and carbon content the amount of CO_2 sequestrated per year due to increase in biomass stocks can be estimated with unit (t CO_2/t).

Price estimation

Historical stumpage price data was collected from the mercantile office of Shafaroud Forest Company during 1996 to 2017. The stumpage price was based on the diameter classes of round wood including <12 cm, 12-15 cm, 16-19 cm, 20-25 cm and >26 cm (Petucco and Andrés-Domenech, 2018). Carbon price was used from carbon traded on European Climate Exchange during 2005 to 2017, because there is not any carbon pricing and trade mechanisms in Iran (Carbon Emissions Futures Historical Prices, 2017; Asante et al. 2011).

There are two possible assumptions to estimate the wood price. First assumption is a stationary autoregressive process; that means changes in one period will have no effect on the price of the next periods. Regression analysis was used to estimate the price equation as below:

$$P_{t+1} = \alpha + \beta P_t \qquad (3)$$

Where, P_{t+1} is price in t+1, α and β are coefficient of regression and P_t is price in time t and $0<\beta<1$.

The second possible assumption is that the price process is non-stationary, which means that the expected price in the next period depends on the price of previous period. According to a non-stationary assumption:

$$P_{t+1} = \beta P_t, \beta < 1 \qquad (4)$$

In general for price equation: $\Delta pt = \Delta P(P_t, \varepsilon t)$ where, ε is a series of random errors with some distribution and autocorrelation zero. In the more restricted first order autoregressive:

$P_t+1 = \alpha + \beta P_t + \varepsilon_t+1$. We assume that ε is a series of normally distributed errors with mean zero and autocorrelation zero. If $0<\beta<1$, then the process P is stationary, with mean of the process:

P_{eq} is expected price, α and β are coefficients (Lohmander and Mohammadi Limaei, 2008;

$$P_{eq} = \frac{\alpha}{1-\beta} \qquad (5)$$

Mohammadi Limaei and Lohmander, 2007). The prices were adjusted by consumer price index (CPI) of Iran for the base year of 2016 according to equation (6) (Central Bank of Iran, 2017).

$$P_I = \frac{P_t \times 100}{Y_t} \qquad (6)$$

Where, P_I is adjusted price, P_t is price in time t, Y_t is the price index in year t and 100 is the value of price index in basic year (Mohammadi Limaei et al., 2013).

NPV of timber and carbon

The real rate of interest was used to determine NPV of timber harvesting and it was considered as 6% in 2017 (Central Bank of Iran, 2017). The rate of carbon considered 3%. Regarding carbon pricing, it is necessary to consider a wide range of possible values, because no definitive real-world observations exist for these parameters. The estimates for the social cost of carbon are dispersed, and prices in existing carbon markets have been very volatile. Over time, the price should perhaps grow with a rate close to the marginal productivity of capital, if mitigation is carried out in a cost-efficient manner. On the other hand, the carbon price growth rate needs to be sufficiently lower than the discount rate, both to keep the objective function of the optimization problem bounded and the approximation of the finite-time problem accurate. In order to ensure the present value remains finite, it is required that the discount rate of timber higher than carbon price growth rate, i.e. that the discounting applied by the forest owner is stronger than the growth rate of the carbon price (Ekholm, 2016). Sensitivity analysis was done for different rate of interest.

The mean basic wood density determined by this study was 0.32 g/cm^3. Conversion factors using basic wood density were used to calculate the carbon proportion per m^3 of volume (Diaz-Balteiro and Rodriguez, 2006) (Table 2).

Faustmann model was used to determine the optimal rotation age (Faustmann, 1849). The first condition of Faustmann's optimization model is maximizing the NPV of plantation in order to determine the optimal rotation age. In other words, the optimal rotation age occurs when the NPV of plantation achieve a maximum value at the infinite series of rotation cycle. That means to maximize the NPV of timber and carbon sequestration. Such that the volume per hectare, volume increment and carbon sequestrated is calculated in duration of trees growth. The NPV is calculated as follows (Diaz-Balteiro and Rodriguez, 2006; Kula and Gunalary, 2012; Mohammadi Limaei et al., 2013; Ekholm, 2016; Keleş, 2017; Namdari et al., 2017):

$$\pi = \mathrm{PV(t)}e^{-rt} + \mathrm{PV(t)}e^{-2rt} + \mathrm{PV(t)}e^{-3rt} + \cdots \qquad (7)$$

$$= \frac{\mathrm{PV(t)}}{\mathrm{e^{rt}} - 1}$$

Optimization:

$$max\left\{\pi = \frac{PV(t)}{e^{rt} - 1}\right\} \quad (8)$$

Derivation:

$$\frac{d\pi}{dt} = \frac{PV'(t)}{e^{rt} - 1} + \frac{PV(t)(-1)(e^{rt})}{(e^{rt} - 1)^2} = 0 \quad (9)$$

Then

$$PV'(t) = \frac{PV(t)e^{rt}}{e^{rt} - 1} = \frac{rPV(t)}{e^{rt} - 1}$$
$$P_{eq}V'(t) = P_{eq}V(t)r \quad (10)$$

Where,

π is NPV of timber and/or carbon at infinite rotation of a plantation,

P is price of timber and/or carbon (Iranian Rials),

P_{eq} is adjusted price of timber and/or carbon at age t (Iranian Rials),

r is timber and/or carbon price (%),

V(t) is the stem volume at age t (m^3/ha),

V'(t) is annual volume increment at age t (m^3),

t is age (year).

The maximization of NPV is obtained after deriving equation (7) and (8) with respect to time and setting the equations equal to zero according to equation (9). After some mathematical manipulations, the necessary condition for the optimal rotation age would be achieved by equation (10). Note, in the solution to equation (10) the maximizing t values respect to optimal rotation age of plantation only if sufficiently condition, i.e., the NPV≥0, is satisfied for timber and carbon (Kula and Gunalay, 2012). The net revenue of timber sell is calculated as a multiplying annual volume (m³/ha) to adjusted price of timber. The net revenue of carbon is estimated as carbon coefficient multiply by annual volume (m³/ha) of plantation by adjusted price of carbon.

Following equation show the NPV for perpetual periodic series:

$$\mathrm{NPV} = \frac{\mathrm{R}}{(1+\mathrm{r})^{\mathrm{t}} - 1} \qquad (11)$$

Where, R is net revenue, r is interest rate (%) and t is age (year).

Equation (11) is changed with regard to plantation cost as follows:

$$\frac{\mathrm{dR_t}}{\mathrm{d_t}} = \frac{\mathrm{r(R_t - C)}}{1 - \mathrm{e^{-rt}}} \qquad (12)$$

Where, R_t is net revenue in year t, r is interest rate (%), C is plantation cost including ploughing, planting and wire fence construction, t is age (year).

If the land value is added to equation (10) the NPV is calculated as follows:

$$\mathrm{P_l V'(t) = r(P_l V(t) + land\ value)} \qquad (13)$$

Where, P_l is adjusted price, L is land value

The NPV of timber (NPV_{Timbr}) and carbon sequestration (NPV_{Carbon}) calculated using the following equation:

$$\mathrm{NPV_{total} = NPV_{Timber} + NPV_{Carbon}} \qquad (14)$$

Results

The forest stand characteristics and growth parameters of 36 years old *Populus deltoides* plantation illustrated in Table 1.

Table 1. Characteristics of the studied Populus deltoides plantation. We show mean ± standard deviation

Tabelle 1. Bestandesbeschreibung der untersuchten *Populus deltoides*-Plantagen. We zeigen Mittelwert ± Standardabweichung

District	Area (ha)	Plantation density (m)	Stem number (N/ha)	dbh (cm)	Basal Area (m^2/ha)	Height (m)	Volume (m^3/ha)
1	66	3m×3m	326	26.59±6.84	13.26±6. 9	19.10±4.10	200.27±0.41
9	43	3m×4m	145	35.67±6.28	7.50±4.9	23.22±3.36	179.36±0.57

Forest carbon sequestration is correlated to volume and biomass growth of forest. The percentage of organic carbon of the 30 analyzed stem and branch samples for each plantation density indicate that mean carbon content in the stem varied from 54.83% to 56.41% at plantation density of 3m×3m and 56.53% to 57.05% at a density of 3m×4m. Contribution of carbon for branches were ranges from 57.14% to 57.56% at plantation density of 3m×3m and it ranges from 55.07% to 58.47% at a density of 3m×4m (Fig. 2).

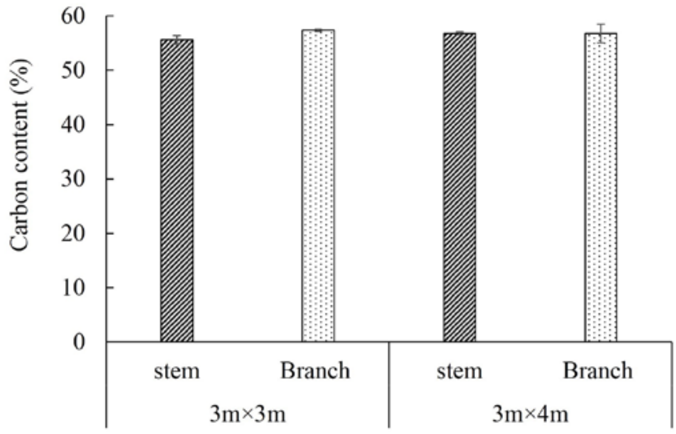


Figure 2: Carbon content in % in stem and branches of Populus deltoides

Abbildung 2: Kohlenstoffgehalt (%) in Stamm und Äste von *Populus deltoides*

The coefficients used in the calculations of economic value are summarized in Table 2.

Table 2. Important coefficients for economic calculations for the two plantation densities. For carbon-volume conversion factor (ratio of total carbon and stem volume) we show in brackets the coefficient of determination of the used regression functions.

Tabelle 2. Wichtige Koeffizienten für die wirtschaftlichen Berechnungen für die zwei Bestandesdichten. Für Kohlenstoff-Volume Konversionsfaktor (Verhältnis von Gesamtkohlenstoff und Stammvolumen) wir zeigen in Klammer das Bestimmtheitsmass.

Coefficient	3m×3m	3m×4m
Wood density (g/cm³)	0.32	0.32
Carbon-volume conversion factor (t carbon/m³)	0.1792 (R^2=0.99)	0.1824 (R^2=0.99)
Interest rate for timber (%)	6	6
Interest rate for carbon (%)	3	3
Adjusted timber price (Iranian million Rials/ton)	0.85	0.85
Adjusted carbon price (Iranian million Rials/ton)	3.40	3.34
Costs of plantation (Iranian million Rials, including ploughing, planting and wire fence construction)	50	50
Land value (Iranian million Rials)	163.2	163.2

Stumpage and adjusted carbon price model

To calculate the cost and revenue we need to know the price of timber and carbon. Since a plantation is a long-term project, it is required to estimate timber prices for a long period.

Stumpage price was estimated according to stationary autoregressive process using equation (3) and carbon price was calculated through the non-stationary using equation (4). The results of regression analysis is illustrated in Table 3.

Table 3. Adjusted price function of stumpage and carbon

Tabelle 3. Angepasste Preisfunktion für Rundholz und Kohlenstoff

Diameter classes of round wood (cm)	Adjusted stumpage price function	Adjusted mean price of timber (Iranian million Rials)
<12	P_{t+1}=151260.8+0.535539 P_t	0.32
12-15	P_{t+1}=569849.6+0.397684 P_t	0.94
16-19	P_{t+1}=709205.7+0.329073 P_t	1.05
20-25	P_{t+1}=631724.8+0.410571 P_t	1.07
	Mean	0.85
	Adjusted carbon price function	Adjusted price of carbon (Iranian million Rials)
	P_{t+1}=0.697554P_t	3.3

Optimal rotation age including NPV of timber and carbon

The NPV of plantation is maximized, when marginal revenue is equal to the rate of interest. Obviously it is not profitable to keep the plantation when the marginal revenue becomes lower than rate of interest. When this plantation age is reached, it is optimal point to harvest the trees and re-establish the plantation (Figs 3 to 6).

Optimal rotation age for timber without considering the value of carbon sequestration for *Populus deltoides* plantations are 10 and 8 years for 3m×3m and 3m×4m plantation density, respectively (Fig 3). Optimal rotation ages including the carbon sequestration values are 14 and 11 years for 3m×3m and 3m×4m plantation density, respectively (Fig. 4).

Optimal rotation ages including the timber and carbon sequestration values are 11 and 9 years for 3m×3m and 3m×4m plantation density, respectively (Fig. 5).

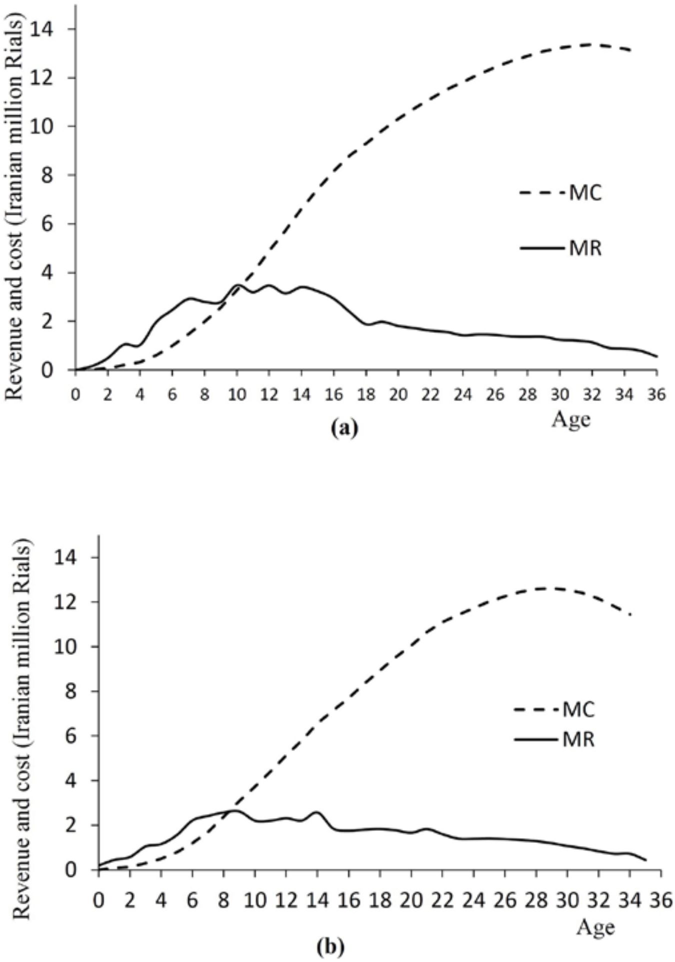
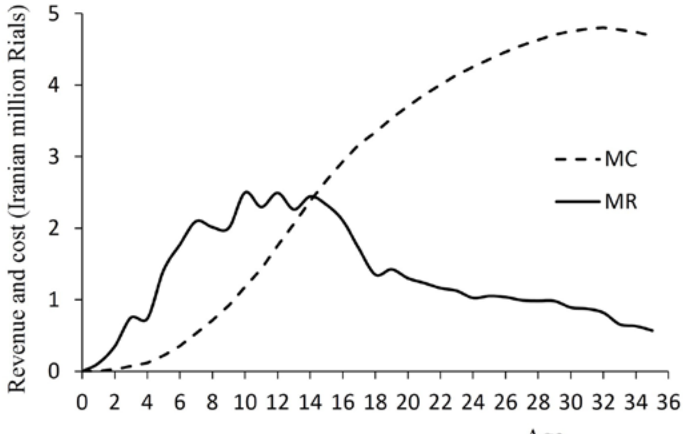
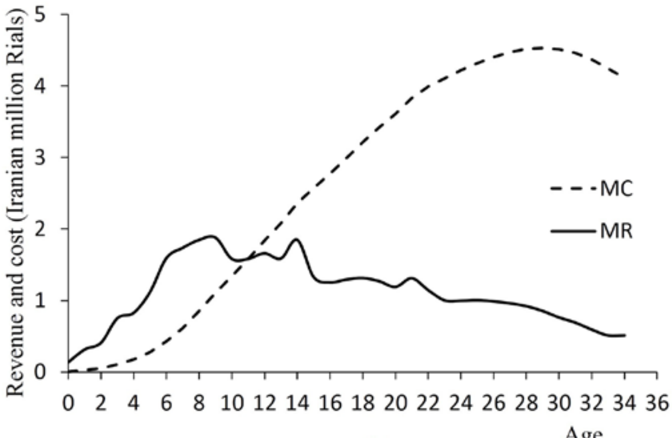


Figure 3: Optimal rotation age for timber in 3m×3m (a) and 3m×4m (b) plantation density (MC: Marginal cost, MR: Marginal revenue)

Abbildung 3: Optimale Umtriebszeit für Holzproduktion bei 3m×3m (a) und 3m×4m (b) Bestandesdichte (MC Grenzkosten, MR Grenzertrag)



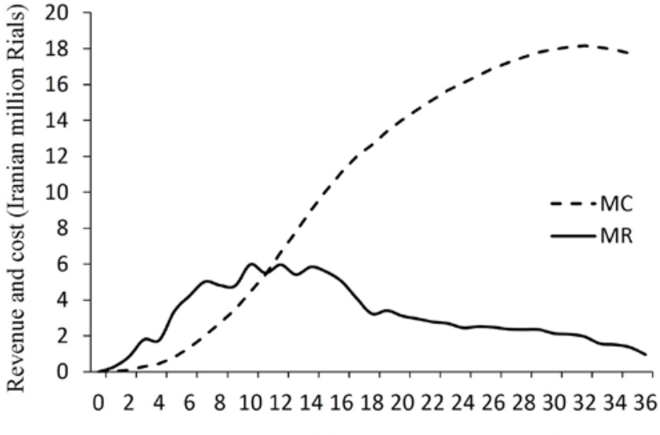
(a)



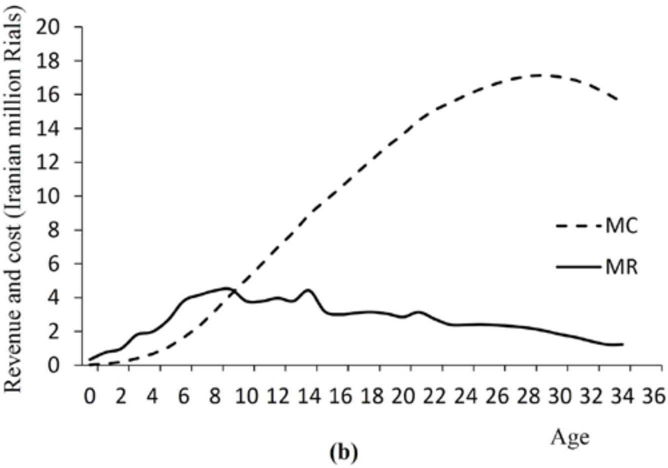
(b)

Figure 4: Optimal rotation age for carbon in 3m×3m (a) and 3m×4m (b) plantation density (MC: Marginal cost, MR: Marginal revenue)

Abbildung 4: Optimale Umtriebszeit für Kohlenstoffspeicherung bei 3m×3m (a) und 3m×4m (b) Bestandesdichte (MC Grenzkosten, MR Grenzertrag)



(a)



(b)

Figure 5: Optimal rotation age for timber and carbon in 3m×3m (a) and 3m×4m (b) plantation density (MC: Marginal cost, MR: Marginal revenue)

Abbildung 5: Optimale Umtriebszeit für Holzproduktion und Kohlenstoffspeicherung bei 3m×3m (a) und 3m×4m (b) Bestandesdichte (MC Grenzkosten, MR Grenzertrag)

Optimal rotation ages considering the plantation cost and land value

Each rotation begins with plantation establishment on bare land and ends with clear cutting. The new rotation starts with the end of the previous rotation. This cycle is repeated infinitely.

Optimal rotation ages considering the NPV of timber considering the plantation costs are 20 and 22 year for 3m×3m and 3m×4m plantation density, respectively (Fig. 6).

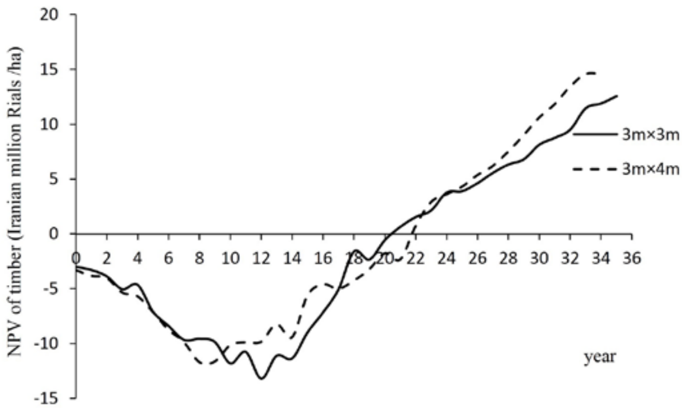


Figure 6: Net Present Value (NPV) of timber of Populus deltoides plantations regarding plantation costs for the two plantation densities

Abbildung 6: Kapitalwert (NPV) der Holzproduktion der *Populus deltoides*-Plantagen hinsichtlich Bestandesbegründungskosten für die zwei Bestandesdichten

Optimal rotation ages considering the carbon sequestration respect to plantation cost are 27 and 26 year for 3m×3m and 3m×4m plantation density, respectively (Fig. 7).

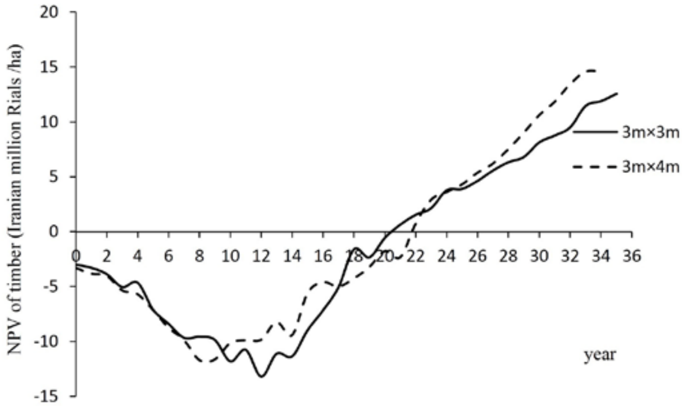


Figure 7: Net Present Value (NPV) of carbon sequestration of Populus deltoides plantations in regard to costs of plantation for the two growing spaces

Abbildung 7: Kapitalwert (NPV) der Kohlenstoffspeicherung der *Populus deltoides*-Plantagen hinsichtlich Bestandesbegründungskosten für die zwei Bestandesdichten

The optimal rotation age considering both timber and carbon values determined using equation (14). NPV of timber and carbon sequestration shown in Fig. 8. Optimal rotation ages for timber and carbon sequestration regarding to the plantation costs are 23 year for both 3m×3m and 3m×4m plantation (Fig. 8).

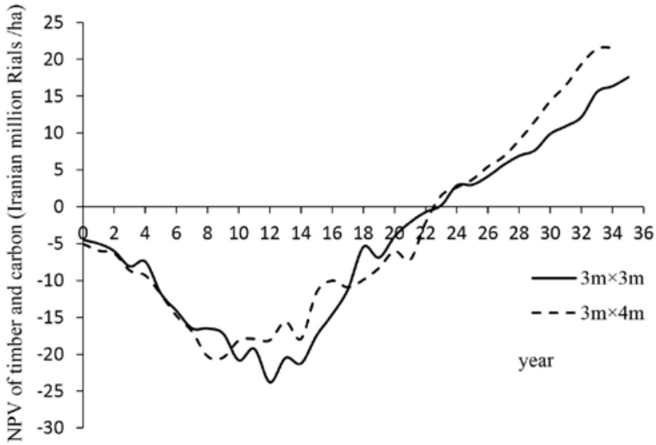


Figure 8: Net Present Value (NPV) of timber and carbon sequestration of Populus deltoides plantations regarding to the costs of plantation for the two growing spaces

Abbildung 8: Kapitalwert (NPV) der Holzproduktion und Kohlenstoffspeicherung der *Populus deltoides*-Plantagen hinsichtlich Bestandesbegründungskosten für die zwei Bestandesdichten

Optimal rotation ages for timber regarding to the land value are 6 years for 3m×3m and 3m×4m plantation density, respectively (Fig. 9).

The negative values of Figs. 6 to 8 show the plantation establishment cost is more than revenue of timber at early years of plantation

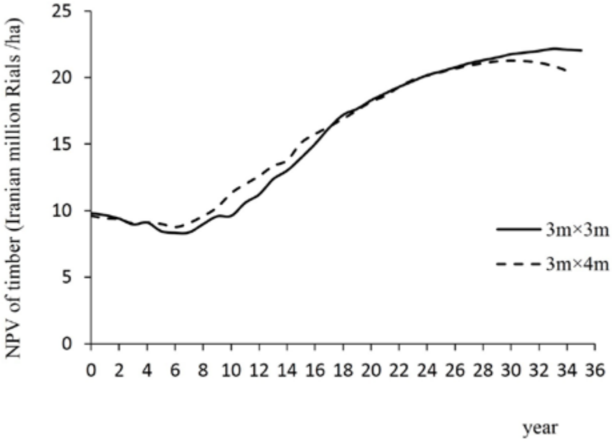


Figure 9: NPV of timber values in Populus deltoides plantations regarding to the land value for two growing spaces

Abbildung 9: NPV der Holzproduktion der *Populus deltoides*-Plantagen hinsichtlich des Bodenwertes für die zwei Bestandesdichten

Optimal rotation ages regarding o the carbon sequestration respect to the land value are 7 and 6 years for 3m×3m and 3m×4m plantation density, respectively (Fig. 10).

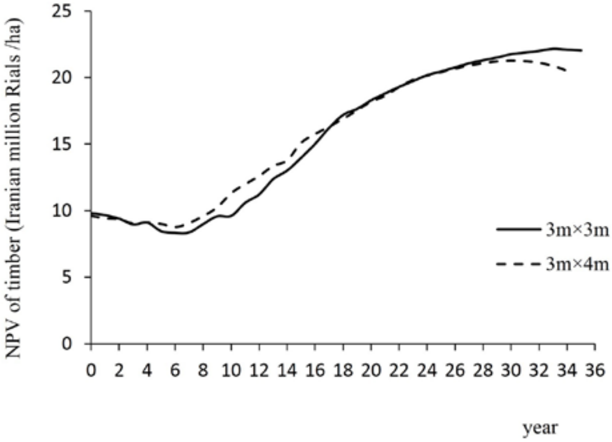


Figure 10: NPV of carbon sequestration of Populus deltoides plantations regarding to the land value for the two growing spaces

Abbildung 10: NPV der Kohlenstoffspeicherung der *Populus deltoides*-Plantagen hinsichtlich des Bodenwertes für die zwei Bestandesdichten

The optimal rotation age considering both timber and carbon values determined using equation (14). NPV of timber and carbon sequestration are shown in Fig. 11. Optimal rotation ages for timber and carbon sequestration regarding to the land value are 7 and 6 year for 3m×3m and 3m×4m plantation density, respectively (Fig. 11).

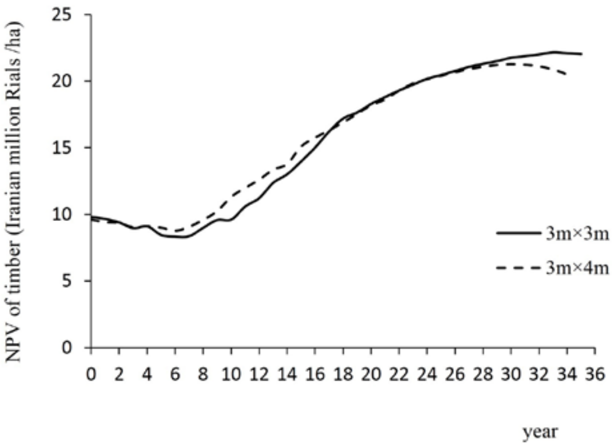


Figure 11: NPV of timber and carbon sequestration values in Populus deltoides plantations considering the land value for the two growing spaces

Abbildung 11: NPV der Holzproduktion und der Kohlenstoffspeicherung der *Populus deltoides*-Plantagen hinsichtlich des Bodenwertes für die zwei Bestandesdichten

Sensitivity analysis

Sensitivity analysis explores how the uncertainty in the output of a mathematical model can be attributed to different sources of uncertainty in its input. utilizing the relationship between input and output variables within a model. Sensitivity analysis helps us to understand how rotation age is sensitive to a change in the plantation cost, land value and rate of interest. The sensitivity parameter values were chosen a set of parameters to check how the model behaves. We show the results of the sensitivity analysis of the optimal rotation age for plantation cost and land value considering interest rate of 6% for timber and 3% for carbon sequestration in Table 4.

Table 4. Sensitivity analysis of optimal rotation age for interest rate, plantation cost and land value for Populus deltoides plantations

Tabelle 4: Sensitivätsanalyse der optimalen Umtriebszeit hinsichtlich Zinssatz, Bestandes-begründungskosten und des Bodenwertes für *Populus deltoides*-Plantagen

Plantation cost (Iranian million Rials)	Rotation age considering timber		Rotation age considering carbon		Rotation age considering timber and carbon	
	3m×3m	3m×4m	3m×3m	3m×4m	3m×3m	3m×4m
20	18	20	24	24	21	22
50	20	22	27	26	23	23
80	22	22	29	27	24	24
110	24	24	30	28	27	26
Land value (Iranian million Rials)						
50	6	6	7	6	7	6
100	6	6	7	6	7	6
200	6	6	7	6	7	6
400	6	6	7	6	7	6
Rate of interest (%)						
1	31	28	31	28	31	28
2	29	27	29	27	29	27
3	26	25	27	26	26	25
4	23	23	24	24	24	23
5	22	22	23	23	22	23
6	20	22	22	22	21	22
7	18	20	21	22	20	22
8	18	20	20	20	19	20
9	18	19	18	20	19	19
10	17	18	18	19	19	19

NPV of timber and carbon for plantation cost, land value and rate of interest in diffe-rent plantation densities shows in Table 5.

Table 5. Summary of NPV of Populus deltoides plantations

Tabelle 5: Zusammenfassung des NPV von *Populus deltoides*-Plantagen

Plantation cost (Iranian million Rials)	NPV of timber (Iranian million Rials)		NPV of carbon (Iranian million Rials)		NPV of timber and carbon (Iranian million Rials)		Definitions
	3m×3m	3m×4m	3m×3m	3m×4m	3m×3m	3m×4m	
20	11.3	9.8	9.6	7.9	20.9	17.7	Timber price
50	13.1	11.6	10.5	8.8	23.6	20.4	(0.85 Iranian
80	14.9	13.4	11.4	9.7	26.3	23.1	million Rials),
110	16.7	15.2	12.3	10.6	29.0	25.8	Carbon prices
Land value (Iranian million Rials)							(3.4 and 3.3 Iranian million Rials), Interest
50	1.5	1.9	0.6	0.3	2.1	4.9	rate of timber
100	8.3	8.7	3.3	3.7	11.6	12.4	(6%) and
200	10.5	10.9	4.4	4.8	14.9	15.7	carbon interest
							rate (3%)
Rate of interest (%)							
1	14.7	12.3	10.7	10.0	25.4	22.3	Plantation cost
2	14.4	11.7	10.6	9.8	25.0	21.5	(50 Iranian
3	14.1	11.7	10.5	9.6	24.6	21.2	million Rials),
4	13.8	11.7	10.4	9.4	24.2	21.0	Timber price
5	13.5	11.6	10.4	9.2	23.9	20.8	(0.85 Iranian
6	13.1	11.6	10.3	9.0	23.4	20.6	million Rials),
7	12.8	11.6	10.2	8.9	23.0	20.5	Carbon prices
8	12.5	11.6	10.1	8.8	22.6	20.3	(3.4 and 3.3
9	12.2	11.4	10.0	8.7	22.2	20.1	Iranian million
10	11.9	11.4	9.9	8.7	21.9	20.1	Rials)

Conclusions

Nonlinear growth functions are commonly used for modelling tree height-diameter When timber harvesting benefits are considered, optimal rotation ages are 10 and 8 years for 3m×3m and 3m×4m plantation density, respectively. Optimal rotation ages including carbon sequestration increased to 14 and 11 years for two plantation densities of 3m×3m and 3m×4m, respectively (Fig. 4). The integration of carbon sequestration benefits into timber production increased the optimal rotation ages of *Populus deltoides* plantations for both plantation density. When both timber and carbon sequestration values are simultaneously considered, the rotation ages are 11 and 9 years for two plantation density of 3m×3m and 3m×4m, respectively (Fig 5). Several studies have shown the optimal rotation age is increased with including carbon sequestration value of forest (Keleş, 2017; Ekholm, 2016; Kula and Gunalay, 2012; Diaz-Balteiro and Rodriguez, 2006). Optimal rotation age in low plantation density is more than the high plantation density. The result is in contrast with results of Keleş (2017).

Including timber harvesting benefits optimal rotation ages regarding to the plantation cost, are 20 and 22 years for the two plantation density of 3m×3m and 3m×4m, respectively. Obtained NPV are 13.1 and 11.6 Iranian million Rials, respectively (fig. 6). Fig. 7 shows the results of optimal rotation ages including carbon sequestration values in two plantation density of 27 and 26 years and NPV are 10.5 and 8.8 respectively. In addition, when the timber and carbon sequestration values were considered the optimal rotation age was 23 year for both plantation densities. The NPV is 23.6 for 3m×3m and 20.4 Iranian million Rials for plantation density of 3m×4m. This means that trees in both stands should stay on the ground longer in order to remove more CO_2 from the atmosphere (Kula and Gunalary, 2012).

Carbon sequestration and timber values are negatively affecting each other. However, when carbon benefits are incorporated into timber value, total net benefit obtained from forest increases with increased carbon benefit over time (Keleş, 2017).

This study also analyzed the effects of various plantation cost, the land value and discount rates on optimal rotation ages including timber and carbon sequestration benefits in two plantation densities (Table 4). When the plantation cost increased, optimal rotation ages considering timber value, carbon sequestration value and timber and carbon values also increased (Table 4). Optimal rotation age is insensitive to the land value (Table 4). The NPV of land value for two growing spaces are shown in Figs. 9 to 11. Results showed that when the rate of interest increased optimal rotation age decreased. In addition, when the interest rate decreased the optimal rotation age increased (Table 4).

Total NPV obtained from timber and carbon sequestration benefits decreased depending on the increase in interest rate (from 1 to 10 %). For example, when the unit of interest rate is increased from 1 to 2%, total net present value increase from 14.7 to 14.1 Iranian million Rials/ha. While the optimal rotation age is decreasing from 31 to 29 years. These values are comparable with the findings of Diaz-Balteiro and Rodriguez (2006), Kula and Gunalary (2012), Mohammadi Limaei et al. (2013), Ekholm (2016), Keleş (2017), Namdari et al. (2017) and Nghiem (2014). Timber price was constant in the calculation of NPV, and it can be analyzed a varying carbon price also for timber. The bases for timber and carbon pricing are quite different.

An efficient mitigation strategy would be associated with increased carbon sequestration by forests through lengthened rotation ages, and also land being valued by its ability for capturing and storing atmospheric carbon.

The effect of various rate of interest on optimal rotation ages is analyzed. Result of sensitivity analysis shows, under constant timber and carbon pricing, by increasing the rate of interest, the optimal rotation age is decreased (Table 4) (Diaz-Balteiro and Rodriguez, 2006; Kula and Gunalary, 2012). A huge decline occurs in the natural forests of Iran in the past few decades. The forests are threatened by a combination of many factors including overpopulation, overconsumption, overexploitation etc. The utilization of natural forests of Iran has been stopped in order to protect and restore the forests. Therefore the wood industries are facing problem for shortage of raw materials. To meet the wood demand, it has been attempted to develop plantations of Populous deltoides as a fast growing species or wood farming in various parts of Iran. Populous deltoides is widely grown in Iran during the last 4 decades due to its fast growing habit, compatibility with agriculture crops and high industrial requirements. The poplar wood is used for many industries such as plywood manufacturing, pulp and building material. Due to its fast growth and wider adoptability, the tree has huge potential to sequester carbon and mitigate CO_2 from the atmosphere. A target of Kyoto Protocol is investment in forestry projects to combat global warming. Plantation with fast growing species is an effective and economical efficient way to achieve this goal.

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