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Evaluation of bioenergy potential and relative impact of microclimate conditions on fuel pellets production and carbon storage of short-rotation coppices (*Populus euramericana*) in reclaimed land, South Korea: Three-year monitoring

JiHwi Jang [1], SuYoung Woo [1,*], SeongHan Lee [1,2], SunMi Je [1,3], Inkyin Khaine [1], Yang Li [1], JongKyu Lee [1], and JiEun Kim [1]

[1] Department of Environmental Horticulture, University of Seoul, Seoul 02504, Republic of Korea; jangjihwi@naver.com (J.H.J.); inkyinkhainefd@gmail.com (I.K.); liyyyyang@naver.com (Y.L.); gpl90@naver.com (J.K.L.); amarg@naver.com (J.E.K.)
[2] Asian Forest Cooperation Organization, Seoul 07236, Republic of Korea; earlymay1004@yahoo.com (S.H.L)
[3] Department of Forest Conservation, National Institute of Forest Science, Seoul 02455, Republic of Korea; jesm0211@korea.kr (S.M.J.)
* Correspondence: wsy@uos.ac.kr; Tel.: +82-2-6490-2691

Abstract: It is required to manage sustainable Short-Rotation Coppices (SRCs) as an important role on carbon sink and bioenergy output, because most of SRCs were established in reclaimed land in South Korea. However, during the last three years, growth pattern of the SRCs was remarkably changed with soil condition. This study aimed to identify the sustainability of SRCs on carbon storage, biomass and fuel pellet production, monitoring the neighboring vegetation of SRCs by land-use exchange, physiological change of poplar on seasonal trend, and to evaluate whether poplar is suitable for making wood pellets. The calculated biomass yield per area of poplar grown was 103.07 Mg per total area (55.6 ha), and volumes of carbon dioxide absorption was estimated to be 330 Mg CO_2. Wood pellet quality based on the criteria scored third grade, indicating that poplar is suitable for manufacturing fuel pellets. Moreover, monitoring of the flora distribution in SRCs revealed changes in species composition. As halophyte was increased during drought, soil organic matter, net growth and total chlorophyll of poplar were significantly decreased. These findings indicated that photosynthesis and growth pattern of SRCs may be negatively affected by microclimate and will provide valuable information for effective management of SRCs.

Keywords: biomass yield; carbon storage; growth pattern; poplar; short-rotation coppices; seasonal trends

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1. Introduction

Soaring energy consumption, increasing greenhouse gas (GHG) emissions, and concerns over energy import dependence are prompting global changes in the sources from which energy is expected to be derived in the coming years [1,2]. In South Korea, adoption of the renewable energy portfolio standard (RPS) started in 2015 (3.5%) and has been increasingly adopted in 2017 (5%) and has been estimated to increase by 10% in 2022. Moreover, the Korea Emissions Trading Scheme (K-ETS) was formally launched in January 2015, aiming for a 30% reduction in South Korea's carbon emissions by 2030 from the business-as-usual levels [3]. Moreover, based on the Paris Agreement adopted at the Conference of the Parties 21 (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC) in 2016, new climate regime (Post-2020), the advanced and developing countries, including South Korea, agreed to work together on GHGs reduction and its technological development was launched. So, the roadmap for reducing greenhouse gas (GHG) was clarified based on the Paris Agreement. In the case of South Korea, a roadmap for reducing GHG has been set up to achieve a 37% reduction compared to the emission target of 2030, which is the Intended Nationally Determined Contribution (INDC).

The production of bioenergy in the form of wood pellets was increased in South Korea because wood pellets were shown to be a renewable energy source [4]. Lee and Kang [5] have reported the effectivity of GHG reduction using biofuel via forest resources. The substitution and enhancement effect of switching from Bunker-C oil to woody biomass fuels (wood pellets and chips) reduced GHG emissions (1.04 kg CO_2 USD^{-1} $year^{-1}$ when converting to pellets and 1.16 kg CO_2 USD^{-1} $year^{-1}$ when converting to wood chips). When switching from kerosene to woody biomass fuel, the GHG reduction effect is 0.53 kg CO_2 USD^{-1} $year^{-1}$ when converting to pellets and 0.54 kg CO_2 USD^{-1} $year^{-1}$ when converting to wood chips; thus, the effect of converting to wood chips appears to be slightly higher than that of converting to pellets [5] (Table 1). The short-rotation coppice (SRC) method of cultivating poplar (1- to 5- year rotation) in plantation is a successful method for growing large amounts of biomass in a short period on plantations [6–11]. Therefore, Korea Forest Service established "Development planning for SRC culture in Saemangeum reclaimed land" for biomass production and as a solution for the limited land area available for plantations in Korean peninsula [12] and launched afforestation project since 2012 [13] in Gimje city (Fig. 1). Woody plants have much more biomass potential than herbaceous plants and therefore can produce valuable new resources, such as timber and wood pellets, to generate energy for heating [14]. Saemangeum area, our study site, has the longest sea dike (33.9 km) and one of the large reclaimed area (8,570 ha) in the world [13]. In 1991, a great project commenced in the western coast of South Korea, never tried in the world history, was launched, constructing embankment for blocking water and inside development will be ongoing until 2020 [13,15].

However, drought is major environmental constraints on forest productivity [16] and South Korea is no exception [17]. Many environmental stresses negatively impact the growth and development of plants, and thereby affect the quantity and quality of crops produced. Drought is one of the most important environmental stresses that alter plant water status [18] and severely limit plant growth and development as well as high salinity on reclaimed land [19–20]. Woody crops alter their use and allocation of nutrients in response to drought, and changes in soil nutrient cycling and trace gas flux (N_2O and CH_4) are observed when experimental drought is imposed on forests [21]. In our meteorological monitoring in recent three years after afforestation, the Saemangeum reclaimed land had harsh summer conditions with minimal soil moisture, high temperature, high incoming solar radiation and little precipitation, especially in 2015. In general, surrounding ocean exert a strong maritime influence, and rainfall is highly regional [22,23], so period of widely distributed low rainfall are unusual in the climatic record [24]. However, reclaimed land usually has the problem relative with temporary drought and fertility even if they are costal reclaimed area such as western coastal area nearby the Yellow Sea in South Korea [15]. Besides, there was a nationwide drought due to a blocking high-pressure system preventing rainfall across the country leading to the worst drought during the last three years in Asia-Pacific region [23,25] since the 1945–1946 season [26], and South Korea was no exception on unusual drought conditions which means a period of sustained dry weather during the summer (November to October) of 2014–2015 [17]. In terms of meteorological monitoring, drought can be defined as soil moisture deficit caused by insufficient rainfall [27]. Even if the reclaimed land contained high levels of soluble salts and exchangeable sodium that hindered plant growth and reduced fertility during the early stage of reclamation project [28], the pedospeheric condition in there has been purified through a desalinization process, such as abundant rain or mixing soils and fast-growing tree plantation [13,29]. However, during recent drought and heat wave in this site, resalinization was temporarily raised as a major environmental stress on growth and development of woody plant. The study of stress response in tree species like poplar is important because of long-lived and ability to absorb problematic ion, adapting to environmental stress [16].

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For these reasons, it is also required to monitor the pedoecological changes and soil nutrient in Saemangeum area of South Korea and to evaluate whether this area is suitable for bioenergy production sustainably.

Given the importance of biomass production and sustainable management SRC in Saemangeum area, the biggest afforested area for producing biomass in South Korea, even harsh climatic condition, the aim of this study were (1) to estimate biomass production and carbon storage in SRCs, (2) to evaluate wood pellet quality and suitability of dry mass yield of poplar trees grown in SRCs, and (3) to determine how changing land use, such as the establishment of SRCs, affects flora distribution in the neighboring vegetation on extremely changed pedospheric and meteorological conditions. We explored variation in soil condition on different SRC types and meteorological condition on wet (moderate) and drought (temporary drought) across the annual cycle for three years and identified annual biomass yield and wood pellet productivity in environment variable for sustainable SRC management.

Table 1. Greenhouse gas (GHG) reduction effectiveness in fuel switching from Bunker-C oil and kerosene to wood biomass [5].

GHG[1] reduction project (Boiler fuel switching)	Investment cost (million USD[2])	Annual GHG reductions (Mg CO_2 year $^{-1}$)	Annual GHG reduction effect (kg CO_2 USD^{-1} $year^{-1}$)
From B-C oil to Wood pellet	6.41	6,702	0.14
From B-C oil to Wood chip	9.12	10,604	0.16
Sum	15.54	17,306	0.30
From Kerosene to Wood pellet	1.11	595	0.53
From Kerosene to Wood chip	13.15	7,071	0.54
Sum	14.26	7,666	1.07

[1]GHG, greenhouse gas; [2]USD, United States dollar

2. Materials and Methods

2.1 Site Description and Microclimate

To embark in an afforestation work for domestic production of bioenergy and SRC business undertaking, Korea Forest Service leased a piece, designated area for land substitution (1,000 ha), of Saemangeum reclaimed land (8,570 ha) on moderate terms from Saemangeum Development and Investment Agency, Sejong city, Korea [13,15]. The University of Seoul research team obtained some study plots in this area to monitor forest production and ecophysiological changes for 3 to 4 years. The total afforested area (SRC) in this site is 55.6 ha. Afforestation was conducted in 2012 (2.3 ha), 2013 (19.0 ha) and 2014 (34.3 ha), respectively. The experimental site in there was selected based on biomass yield for producing wood pellets and was situated in the SRC culture on reclaimed land that is part of the marginal lands in the Saemangeum land reclamation project area in Gimje City, Jeollabuk-do Province in Korea at 35°52′N and 126°47′E (Figure 1).

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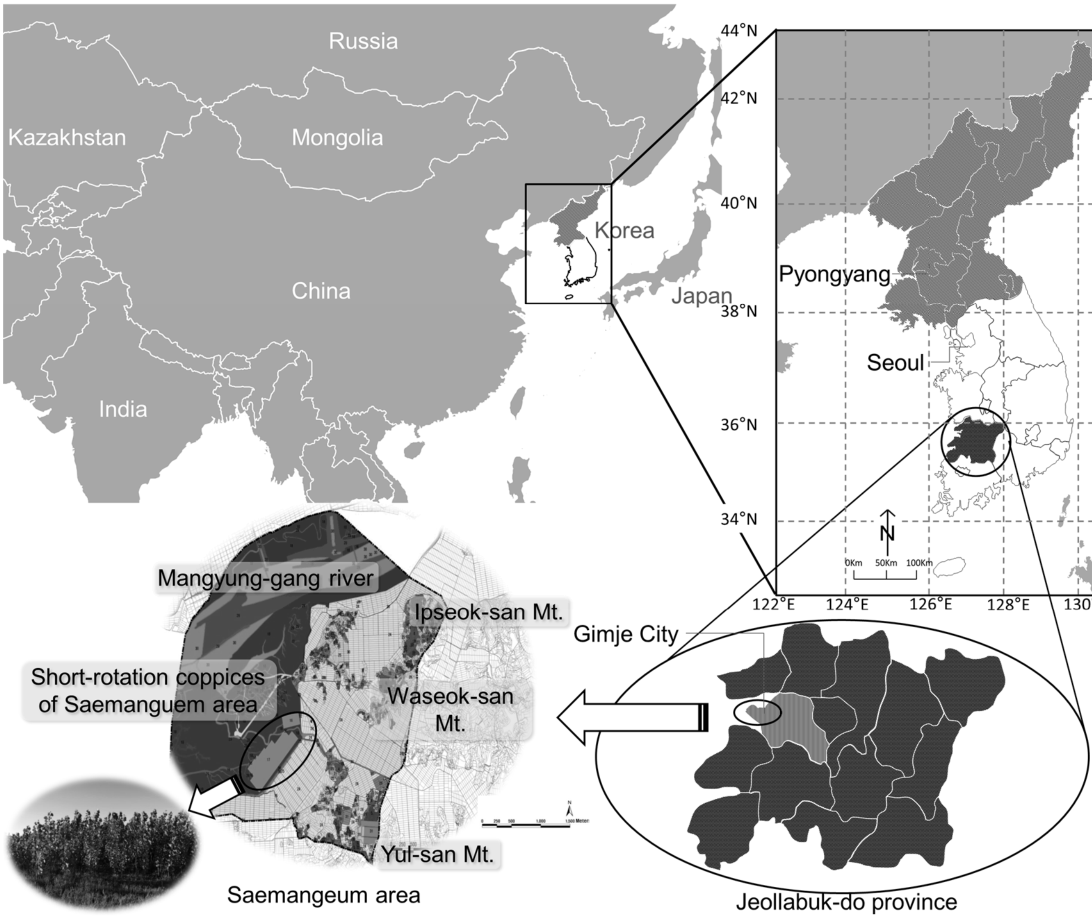

126 **Figure 1.** Site description of short rotation coppice in Saemangeum reclaimed land, South Korea.

127 At this site, the annual rainfall and mean air temperature are approximately 827 mm and 13 °C
128 (maximum: 32 °C, minimum −7 °C), respectively and rainfall is summer dominant, however summer
129 rainfall in 2015 was very lower than other periods (Figure 2).

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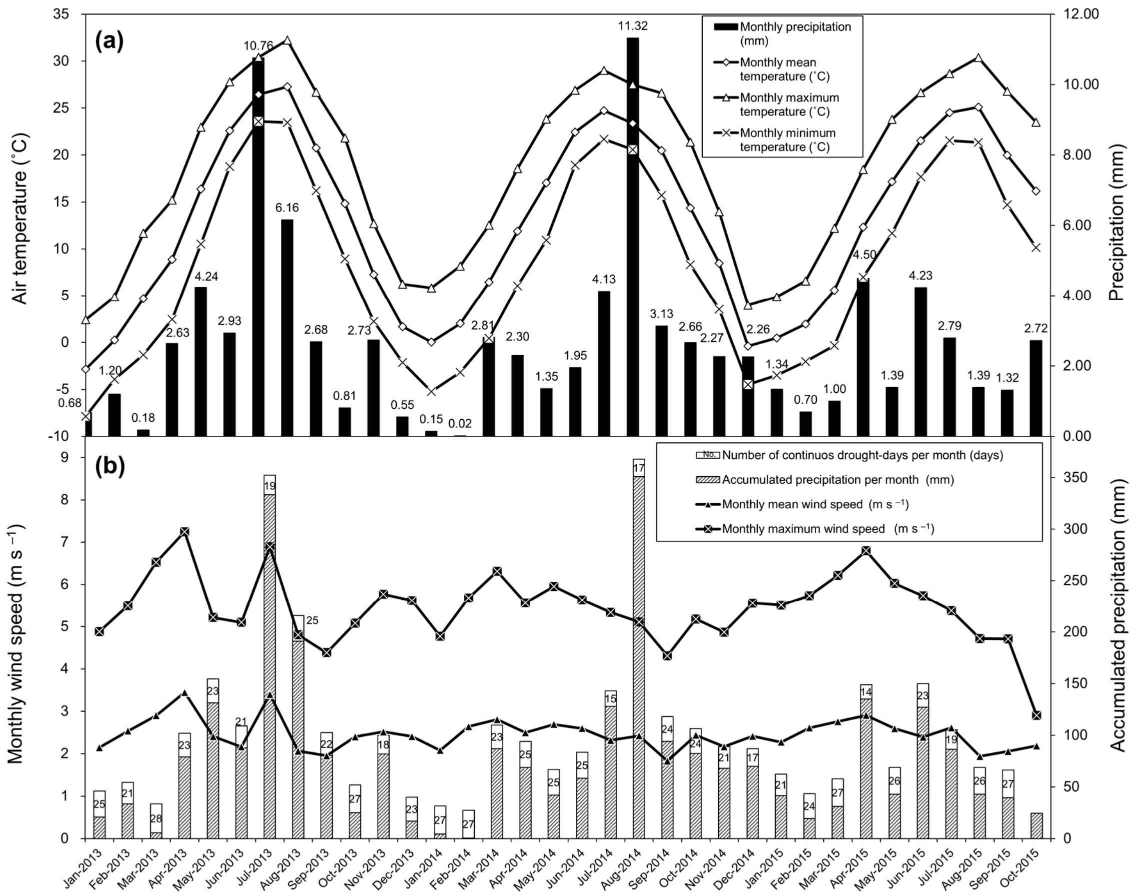

Figure 2. Weather condition of short rotation coppice in Saemangeum reclaimed land, South Korea. (**a**) Monthly air temperature and precipitation; (**b**) monthly wind speed, drought days and accumulated precipitation for the study site throughout 2013, 2014 and 2015.

Relative humidity (RH) and air temperature in this study site were monitored and logged automatically from June to October 2015 using one HOBO pro RH/Temp Data loggers and External temp Data Loggers (On-set computer Co., Porasset, MA, USA). The data recordings were taken at one hour intervals. The other meteorological data in experimental plot was collected from January 2013 to October 2015 by Korea Meteorological Administration (KMA), National climate data service system (Figure 3). The collected data from KMA were as follows: 1) Monthly precipitation, 2) Monthly mean temperature, 3) Monthly maximum temperature and 4) Monthly minimum temperature 5) Global radiation.

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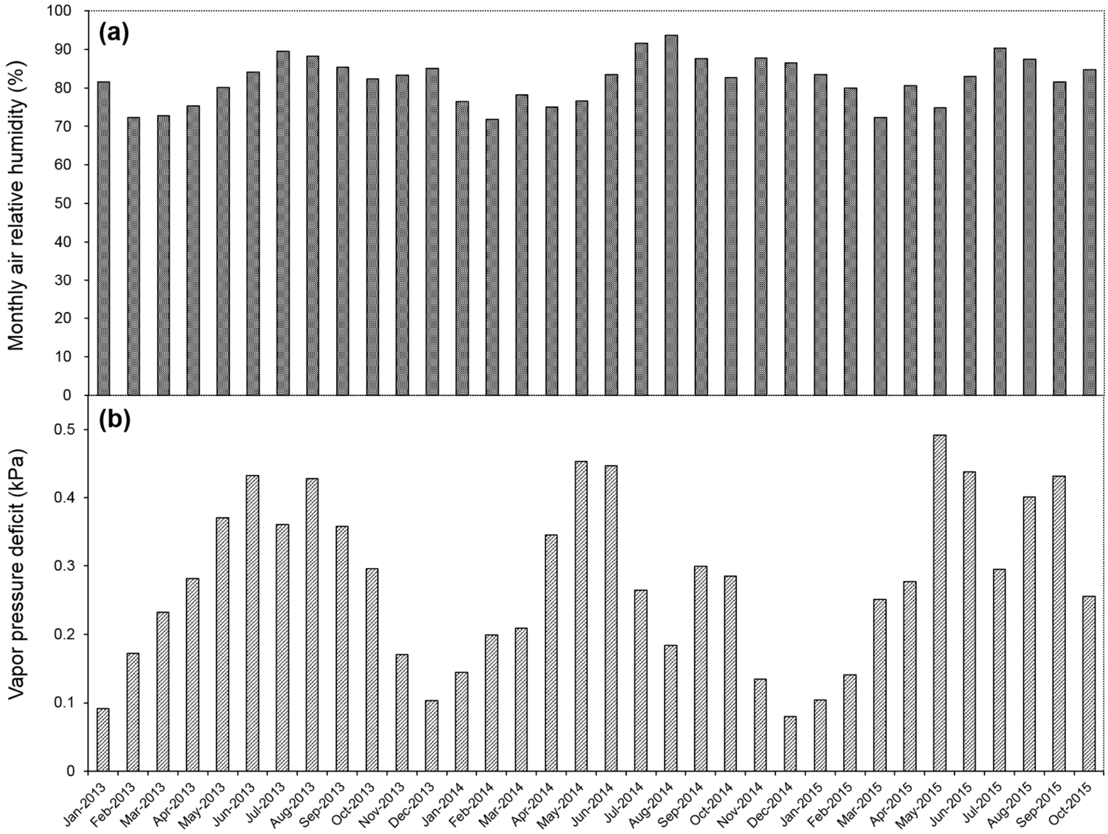

Figure 3. Weather condition of short rotation coppice in Saemangeum reclaimed land, South Korea. (**a**) Relative humidity; (**b**) vapor pressure deficit for the study site throughout 2013, 2014 and 2015.

The global radiation was converted into a photosynthetic photon flux density (PPFD, μmol m^{-2} s^{-1}) using the conversion factor (2.2359) based on the following equation [30], PPFD was calculated the method of Suh [30] (Figure 4). At this site, global radiation and mean photosynthetic photon flux density are approximately 19.3 MJ m^{-2} d^{-1} and 498.3 μmol m^{-2} s^{-1} (maximum: 983.4 μmol m^{-2} s^{-1}, minimum 17.9 μmol m^{-2} s^{-1}), respectively. The photon flux density was determined using the following formulae (Equation (1)):

$$PPFD = 2.2359 \times I \ (r=0.9948) \quad (1)$$

Where PPFD is photosynthetic photon flux density, I is global radiation.

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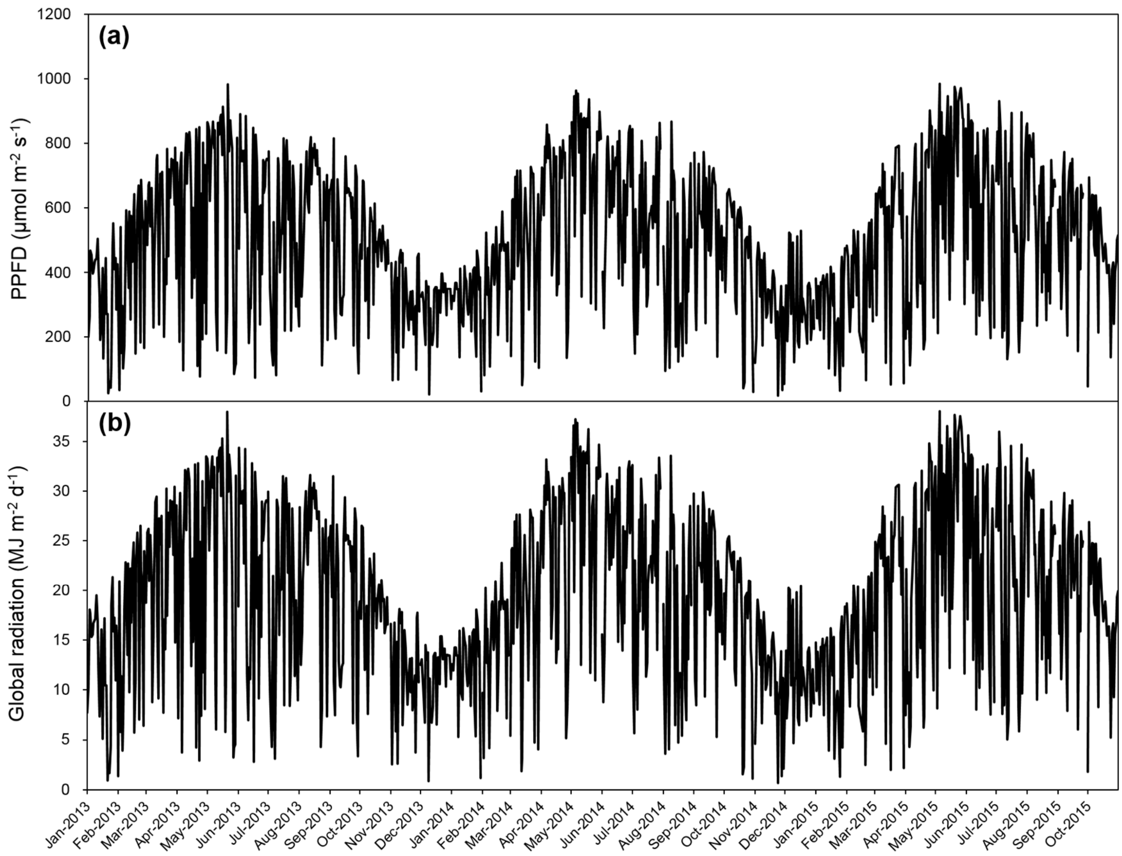

Figure 4. Weather condition of short rotation coppice in Saemangeum reclaimed land, South Korea. (**a**) Photosynthetic photon flux density; (**b**) global radiation for the study site throughout 2013, 2014 and 2015.

2.2 Biomass and Carbon Estimation

Italian poplar (*Populus euramericana*), which is known to be suitable for reclaimed land in South Korea [31], was used in this study and was planted on site in 2012, 2013 and 2014. To estimate the biomass yield of poplar, we measured the diameter at breast height (DBH) of trees in sample plots (10 × 10 m) in the area (four plots per 0.1 ha) and classified DBH values as minimum, median, and maximum. Poplar trees in the sample plots were subsequently harvested in October 2013, 2014 and 2015, respectively, and oven-dried to a constant weight (oven DS-80-2, Dasol Science, Korea) at 70°C for 96 h; the dry weight of the leaves, stems, and branches was then measured [32]. Total biomass (Oven-dried tonnes, ODT) was obtained based on these data according to formula on estimation of aboveground biomass (Equation (2)), where A and B are coefficient of the regression parameter to be determined, D is the DBH (mm) and y is the dry weight of aboveground mass (ODT ha^{-1} yr^{-1}). Stem, branch, and leaf biomass was obtained based on these data, and root biomass was calculated by the method of Caims et al. [33] and Noh et al. [34] (the root biomass is 35% (carbon fraction) of the biomass aboveground). The coefficient estimation method is based on biomass data collected in October 2013, 2014 and 2015, respectively. The root biomass was determined using the following formula (Equation (3)):

$$y = A \times e^{BD} \quad (2)$$

$$\text{Root biomass (Mg)} = S + B + L \times 0.35 \quad (3)$$

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Where A and B are coefficient of the regression parameter to be determined, y is the dry weight of aboveground biomass of poplar trees, D is diameter at breast height, S is dry weight of poplar stem, B is dry weight of poplar branch, L is dry weight poplar leaf.

To investigate the potential of carbon storages in SRCs, it was analyzed the carbon content (%) of the biomass and multiplied with the dry mass. Poplar tree samples were chipped and broken down using a crusher and air-dried at room temperature. The material was then sorted into powder using 60–80 mesh (testing sieve grid area: 1 mm) and 40–60 mesh (testing sieve grid area: 425 μm). The carbon contents of poplar samples grown in SRC of reclaimed land were analyzed via an elemental analyzer (Flash EA 1112, Thermo, USA). The amount of CO_2 absorption was also calculated by using their molecular weight [35]. It is generally known that carbon content (carbon fraction) of woody plants studied in previous studies is 50% of drymass of them [36–39]. However, biomass and carbon coefficient can be changed in many ways on environment and various condition even if there are same species [40]. Thus, we analyzed carbon content of poplar grown in Saemangeum reclaimed land, and used this value (average 46 %) as a coefficient for estimating carbon storage of poplar trees. The formula we used is as follows: Carbon storage (gC) = Total biomass × 0.46 (carbon content of poplar, %), Carbon dioxide absorption volume (gCO_2) = carbon storage × 44 (molecular weight of carbon dioxide) × [12 (molecular weight of carbon)]$^{-1}$ (Equations (4,5)).

$$\text{Carbon storage (gC)} = \text{T (g)} \times 0.46 \tag{4}$$

$$\text{Carbon dioxide absorption volume (gCO}_2\text{)} = \text{T (g)} \times 0.46 \times 44/12 \tag{5}$$

Where T is dry weight of aboveground biomass of polar trees.

2.3 Change of Neighboring Herbaceous Vegetation

To investigate the plant diversity and flora distribution around the SRC, we monitored changes in the actual vegetation and the structure of the herbaceous vegetation in plots (5 × 5 m) in the area (from 5 to 9 plots per 0.1 ha in the SRC) planted with *P. euramericana* and in neighboring vegetation of SRC, respectively. Based on collected data, we classified type of the plant occurred in SRC and its neighboring vegetation, and investigate dominant species in each site, frequency of occurred plant, their relative density, and number of plants per ha. All data were calculated by the method of Braun-Blanquet and Taylor [41,42]. The formula we used is as follows: Frequency (F, %) = [number of plots appeared specific species] × [number of total plot (5m × 5m) in filed site]$^{-1}$ × 10^2. Relative density (RD, %) = (number of specific plant species among all plot of specific site) × (number of total species appeared in all plot of specific site)$^{-1}$ × 10^2. Number of plant per ha (n, EA ha^{-1}) = [the number of specific plant species appeared in all plot of specific site] × [(the number of specific plant species appeared in all plot of specific site) × (the number of plots × plot area (5m × 5m))$^{-1}$]$^{-1}$ × 10^4 (Equations (6–8)).

$$\text{F (\%)} = N_{AS} \times N_T \times 10^2 \tag{6}$$

$$\text{RD (\%)} = N_{SS} \times N_{TS} \times 10^2 \tag{7}$$

$$\text{N (EA ha}^{-1}\text{)} = (N_T \times N_{PS})/(N_P \times 25) \times 10^4 \tag{8}$$

Where F is frequency, N_{AS} is number of plots appeared specific species, N_T is number of total plot in filed site, RD is relative density, N_{SS} is number of specific plant species among all plot of specific site, N_{TS} is number of total species appeared in all plot of specific site, N is number of plant per ha, N_T is the number of specific plant species appeared in all plot of specific site, N_{PS} is the number of specific

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plant species appeared in all plot of specific site, N is the number of plots, N_T is the number of specific plant species appeared in all plot of specific site, N_{PS} is the number of plots.

2.4 Energy Value and Pellet Criteria

Harvested poplar tree samples were chipped and broken down using a crusher and air-dried at room temperature. The material was then sorted into powder using 60–80 mesh (testing sieve grid area: 1 mm) and 40–60 mesh (testing sieve grid area: 425 μm). It is known toxic chemical substance emission is problematic because of increased contents of N, Cl, S, and heavy metals when fuel pellets burn. To evaluate their contents, this parameter (%) was chosen following the Korean criteria for wood pellet quality [43], Pellet Fuels Institute standard specifications of United States [44], and EN-Plus standard specifications of European Union [45]. Each of those standards defines three or four quality classes: 1st grade (G1 or Premium, A1), 2nd grade (G2 or Standard, A2), 3rd grade (G3 or Utility, B), and 4th grade (G4) based on the range values of specific parameters, with ash content or calorific value as the most important. The physical and chemical parameters (toxic substance emissions) were taken into account in this study are shown in Table 2. Specific analyze assay on pellet criteria were calculated by the method and equipment employed of Jang et al. [29] with isoperibol oxygen bomb calorimeter (Parr 6400, Parr, IL, USA), electric muffle furnace (J-FM3, JISICO, Korea), inductively coupled plasma (Atomscan 25, USA), ion chromatography (Sykam S-134) and an elemental analyzer (Flash EA 1112, Thermo, USA) (Equations (9, 10)).

$$Q_d \text{ (MJ kg}^{-1}) = Q_{dm}/m_{ds} \quad (9)$$

Where Q_d is the net calorific value per weight of measured dry mass, Q_{dm} is the calorific value of the measured dry mass, and m_{ds} is the dry weight of the measured sample.

$$\text{Ash (\%)} = \text{W (g)/D (g)} \times 100 \quad (10)$$

Where Ash is ash content of drymass, W is weight after oxidation of sample, D is dry weight of sample.

Table 2. Specifications for Korean wood pellet quality criteria according to National Institute of Forest Science standard specification (KR), Pellet Fuels Institute standard (US), and EN-Plus standard (EU) [29]

Specification		Q	Ash	N	Cl	S	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
		≥ (MJ kg⁻¹)	≤ (%)				≤ (mg kg⁻¹)							
KR	G1	18.0	0.7	0.3	0.05	0.05	1.0	0.5	10	10	10	0.05	10	100
	G2		1.5	0.5										
	G3	16.9	3.0	0.7										
	G4		6.0	1.0										

	P		1.0	NA										
US	S	NA	2.0	NA	0.03	NA								
	U		6.0	NA										
	A1		0.7	0.3	0.02	0.04								
EU	A2	16.64	1.2	0.5		0.05	1.0	0.5	10	10	10	0.1	10	100
	B		2.0	1.0	0.03									

KR, Republic of Korea; US, United States of America; EU, European Union. G1, first grade; G2, second grade; G3, third grade; G4, fourth grade [43]; P, PFI Premium; S, PFI Standard; U, PFI Utility [44]; A1, EN-Plus-A1; A2, EN-Plus-A2; B, EN-Plus-B [45]; NA, no value has been established.; *Q*, net calorific value; Ash, ash content.

2.5 Volumetric Soil Moisture Content

Soil water content reflectometers (CS616, Cambell Scientific, Logan UT, USA) were installed at two locations to determine soil's volumetric moisture content. Sensors were inserted horizontally at 30 cm below the interface. The data recordings were taken at one hour time steps, and Campbell Scientific calibration equation was used to calculate volumetric moisture content. Volumetric soil moisture content (VSM, %) was very similar for both locations, so only one location is presented in the results (Figure 5).

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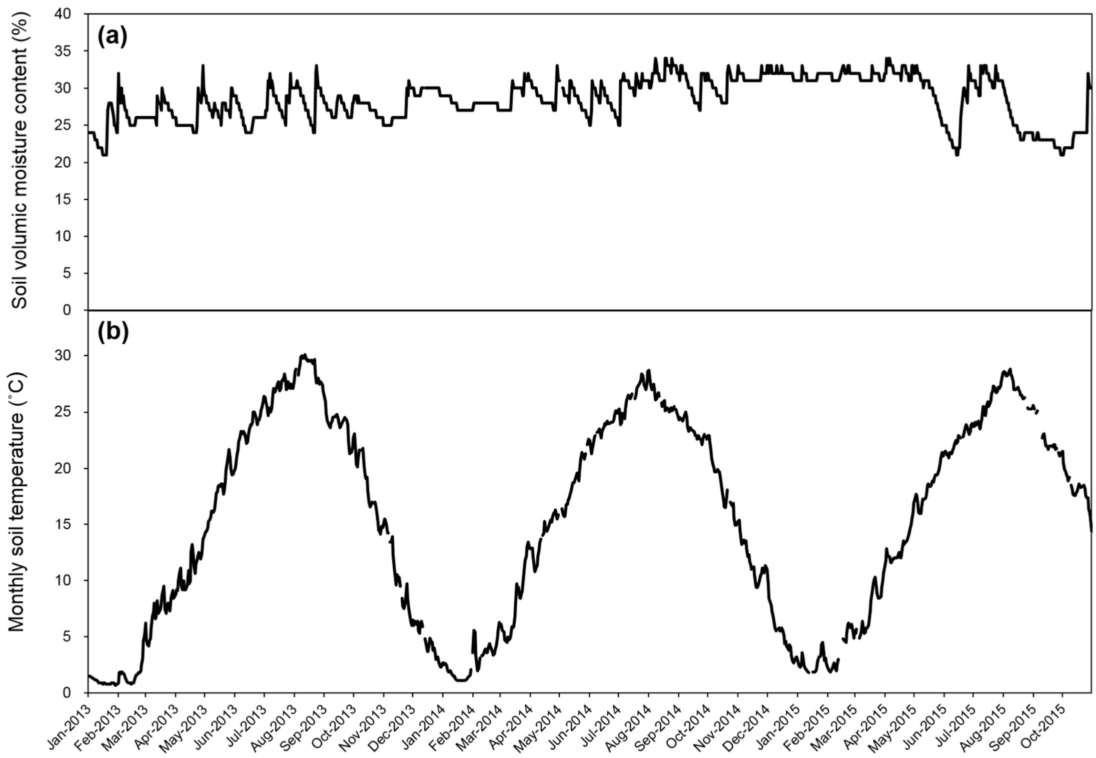

Figure 5. Weather condition of short rotation coppice in Saemangeum reclaimed land, South Korea. (**a**) Soil volumetric moisture content at 30cm below; (**b**) soil temperature at 30cm below for the study site throughout 2013, 2014 and 2015.

2.6 Soil Chemical Properties

Soil samples were collected from the area of the SRC during the experimental period. The sampled soil was oven-dried at 60°C for 48 h, and the oven-dried soil samples were analyzed for their chemical and physical properties. The electrical conductivity (EC) and pH values were determined using EC and pH meters (S230 and MP230, respectively, from Mettler Toledo, Switzerland) at a soil-to-water ratio of 1:5 (w/v). Total nitrogen was determined by the Kjeldahl method with a Kjltec 2300 Auto Analyzer (Foss, Sweden) [46]. Organic matter was determined using the method described by Walkely and Black [47]. Available phosphorus was determined by the method of Bray and Kurtz [48] (Equations (11)).

$$\text{Total nitrogen (\%)} = (T - B) \times f \times N \times 14 \times 100\ w^{-1} \times 100\ s^{-1} \tag{11}$$

Where T is standard solution of sulfuric acid (ml), B is standard solution of sulfuric acid for using blank titration (ml), f is correction value of standard solution of sulfuric acid, N is normality of standard solution of sulfuric acid, w is weight of sample (mg), s is the mount of used filtrate (ml)

2.7 Quantification of Photosynthetic Pigments

To investigate foliar photosynthetic pigment measurements, poplar leaves were collected in June and October 2013, 2014 and 2015 to measure the contents of chlorophyll a and b and carotenoid. Chlorophyll (Chl) and carotenoid (Car) were extracted from 0.1 g leaf discs using 10 cm^3 of an 80 % acetone solution in a brown vial for one week at 4°C. Absorbance was measured using a spectrophotometer at wavelengths of 663, 645, and 470 nm with a microplate reader (Epoch, Bio-Tek, USA). Chlorophyll contents (chlorophyll a, chlorophyll b, and total chlorophyll) and total carotenoid were calculated using the method of Arnon [49] (Equations (12–15)).

$$\text{Chlorophyll a (mg g}^{-1}\text{ FW)} = 12.7 \times A - 2.69 \times B \quad (12)$$

$$\text{Chlorophyll b (mg g}^{-1}\text{ FW)} = 22.9 \times B - 4.68 \times A \quad (13)$$

$$\text{Total chlorophyll (a + b) (mg g}^{-1}\text{ FW)} = 20.2 \times B - 8.02 \times A \quad (14)$$

$$\text{Total carotenoid (mg g}^{-1}\text{ FW)} = (1000 \times C - 1.82 \times \text{Chl a} - 85.02 \times \text{Chl b}) / 198 \quad (15)$$

Where FW is fresh weight, A, B and C are pigment concentration, calculated as mg g^{-1} of FW from a 1 g m^{-3} cuvette of extract, A is the absorbance of the extract solution in a 1 cm path-length cuvette at wavelength 663 nm, B is the absorbance at 645 nm, C is the absorbance at 470 nm.

2.8 Statistical Analysis

We used a one-way ANOVA to determine whether pedospheric and meteorological condition on seasonal change affect biomass yield and carbon sequestration during wet and dry years and to determine which physiological and ecological change for 3 years (2013 – 2015). All statistical analyses of experimental data between different environmental conditions were performed with SPSS Statistics version 23 for Windows (SPSS, Chicago, IL, USA). Least significant difference calculations among the mean values were performed by one-way ANOVA and Duncan's multiple range tests at a p value of 0.05. Data analysis in 2013 SRC was done by independence t-test ($P \leq 0.05$).

3. Results

3.1 Biomass, Carbon Storage, and CO_2 Absorption

To estimate the biomass production of poplar, the relationship between DBH and dry mass was established (Table 3), and the following formula was applied to calculate the total biomass per area: sum of trees in plot (5m × 5m) × 10^4 × (number of trees) $^{-1}$ × 10^{-3}.

Table 3. The coefficient of estimated equation for biomass produced in short-rotation coppices in Saemangeum reclaimed land.

Species	RT*	Part of tree	A	B	r^2
		Stem[1]	75.365	0.0796	0.87
Italian poplar	2013	Branch[2]	6.8379	0.1173	0.8167
(*Populus*	(13W)	Leaf[3]	4.8937	0.0865	0.89
euramericana)		Root		([1] + [2] + [3]) × 0.35[a]	
	RT	**Part of tree**	**A**	**B**	**r^2**

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	Stem[1]	58.951	0.0753	0.93
2014	Branch[2]	8.8832	0.0836	0.89
(14W)	Leaf[3]	4.148	0.0768	0.93
	Root	$(^1 + ^2 + ^3) \times 0.35^a$		
RT	**Part of tree**	**A**	**B**	**r^2**
	Stem[1]	86.014	0.0667	0.93
2015	Branch[2]	8.8055	0.078	0.85
(15D)	Leaf[3]	4.549	0.0825	0.93
	Root	$(^1 + ^2 + ^3) \times 0.35^a$		

*RT, rotation of coppices. Total biomass (Oven-dried tonnes, Mg) was obtained based on these data according to [$y = A \times e^{BD}$], where A and B are coefficient of the regression parameter to be determined, D is the DBH (mm) and y is the dry weight of aboveground (oven dry tons (Mg) ha^{-1} yr^{-1}). [a]Root biomass [34,35], The coefficient estimation method is based on biomass data collected in October 2013, 2014 and 2015, respectively.

The aboveground biomass in this SRC was estimated to be 103.07 Mg 3yrs $^{-1}$, and the carbon stock and CO_2 absorption volume were calculated to be 89.92 MgC 3 yrs^{-1}, 329.72 $MgCO_2$ 3yrs^{-1}, respectively (Table 4). The biomass production and carbon stock are shown in Table 4.

Table 4. Biomass yield and carbon storage of poplar grown in short rotation coppice in Saemangeum reclaimed land throughout 2013, 2014 and 2015.

Sites	**AR (ha)**	**RT (tree age)**	**MH (m)**	**MD (cm)**	**Biomass (ODT (Mg) ha^{-1})** Stem	Branch	Leaf	Root	Total	**C ($MgC\ ha^{-1}$)**	**CO_2 ($MgCO_2$ ha^{-1})**
		13W[X] (1)	2.8	1.5	3.5	0.8	0.9	1.8	7.02	3.2	11.8
2012[a]	2.3	14W[Y] (2)	4.5	2.9	14.1	3.1	1.9	6.6	25.8	11.8	43.5
		15D[Z] (3)	6.3	4.2	20.2	3.8	2.5	9.2	35.6	16.4	60.1
2013[b]	19	13W (NA)					–				

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		14W (1)	1.8	1.5	1.3	0.5	0.3	0.73	1.5	0.7	2.5
		15D (2)	2.9	2.6	1.9	0.4	0.5	0.9	3.8	1.7	6.5
		13W (NA)						–			
2014[c]	34.3	14W (NA)						–			
		15D (1)	1.3	1.9	0.6	0.05	0.2	0.3	1.2	0.5	2.0
Total	55.6		3.5	2.9	2.9	4.2	3.2	10.5	40.6	18.7	68.6

AR, area; RT, rotation of coppices; MH[c], mean tree height; MD[d], mean diameter at breast height; SRC, short rotation coppice; C, carbon storage; CO_2, Carbon absorption volume; ODT, oven-dried tonnes (Mg), Carbon storage (g C) = Total biomass × 0.46 (carbon content of poplar, %), Carbon dioxide absorption volume (g CO_2) = carbon storage × 44 (molecular weight of carbon dioxide) × [12 (molecular weight of carbon)]–1, All samples were collected in October 2015 except for root biomass.[X]13W, collected data in first rotation with wet season in 2013; [Y]14W, collected data in second rotation with wet season in 2014; [Z]15D, collected data in third rotation with dry season in 2015. [a]2012, plot of short-rotation coppice (SRC) established in 2012 (density, 1 × 1m). [b]2013, plot of short-rotation coppice (SRC) established in 2013 (density, 1 × 1m). [c]2014, plot of short-rotation coppice (SRC) established in 2014 (density, 1 × 1m). "–" means unsprouted and/or unafforested area. NA, no value has been established. One-way ANOVA test was performed to evaluate the differences among three sites (2012, 2013 and 2014). Post hoc comparisons were performed using the Tukey's post test at a significance level of $P \leq 0.05$. Data analysis in 2013 SRC was done by independence t-test ($P \leq 0.05$). Different uppercase letters in the same column (three sites) represent significant differences among three SRC sites (pedospheric condition) of the same meteorological condition at $p \leq 0.05$, Different lowercase letters in the same column represent significant differences among different meteorological conditions (wet and drought of same site) of the same site, Asterisk in the same column represent significant differences among different meteorological conditions and pedospheric condition of the same poplar stand ages (1-year, first rotation), as determined by Tukey's post test. Total chlorophyll, chlorophyll a/b ratio and carotenoid content with less than two different rotation or climate factor were excluded from the statistical analysis.

In SRC 2012, during the three years study, annual net height growth of poplar seedling was highest in 1.03 m yr^{-1} on second rotation (14W), followed by 0.79 m yr^{-1} on third rotation (15D) and 0.78 m yr^{-1} on first rotation (13W) ($P < 0.05$). However, the annual net growth of diameter was not significantly different among three different rotations (Figure 6).

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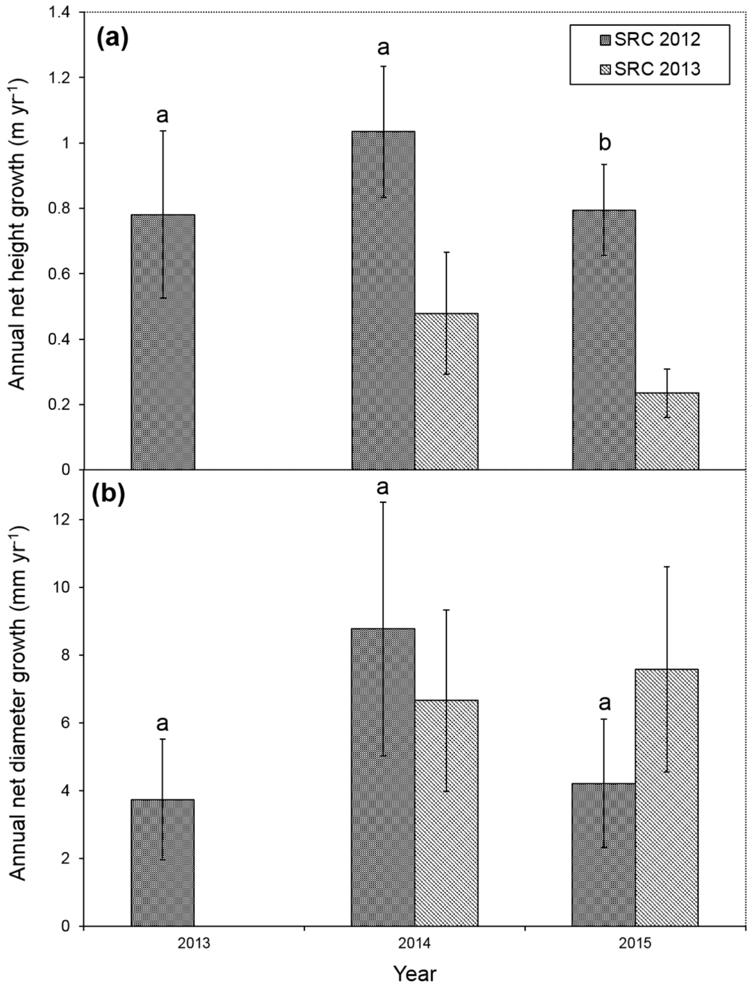

Figure 6. Annual net height growth (a); annual net diameter growth (b) for the study site (SRC 2012, 2013) throughout 2013, 2014 and 2015. Data were analyzed using one-way ANOVA and Duncan's multiple range test. Different letters in the same column represent significant differences at $P \leq 0.05$.

3.2 Fuel Pellet Utilization

Klasnja et al. [50] have reported the calorific values based on drymass of *P. euramericana* are different with those of *P. deltoides* and *Salix alba*. Their results showed that *Populus* wood has the highest heating value for dry mass (calculated for the whole tree based on the proportion of bark). To investigate whether whole wood material, such as wood pellets, is suitable for producing biofuel, we analyzed the net calorific value (*Q*), ash content, and amounts of toxic chemical substance, and heavy metal content of dry mass (Table 5) According to the results, biomass produced at this site yielded third-grade pellets (G3), and its calorific value (*Q*) for generating heating energy was established to be equal to that of first-grade (G1) pellets. All data obtained (*Q*, ash content, N, Cl, S, As, Cd, Cr, Cu, Pb, Hg, Ni and Zn) were very similar for three years (rotation), so only one data analyzed in 2015 is presented in the results.

Table 5. Net calorific value, ash content, toxic chemical substance (N, Cl, S), heavy metal content of dry mass produced in short rotation coppice in Saemangeum reclaimed land

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Q (MJ kg^{-1})	Ash content (%)	N (%)	Cl (%)	S (%)
18.8–19.4*	1.20–1.65**	0.94–0.79**	0.0012–0.006*	0.026–0.022*
> 18.0[z]	< 3.0	< 1.0	< 0.05	< 0.05

As	Cd	Cr	Cu	Pb	Hg	Ni	Zn
(mg kg^{-1})							
N.D[a,*]	0.3–0.5*	0.4*	4–5*	0.2–0.4*	N.D[a,*]	N.D[a,*]	18–20*
≤ 1	≤ 0.5	≤ 10	≤ 10	≤ 10	≤ 0.05	≤ 10	≤ 100

*First grade (G1), **third grade (G3), [z]the grade criteria of wood pellet, [a]not detectable (National Institute of Forest Science 2015)[44], *Q* net calorific value, All samples were collected in October 2015 except for root biomass. All data obtained (*Q*, ash content, N, Cl, S, As, Cd, Cr, Cu, Pb, Hg, Ni and Zn) were very similar for three years (rotation), so only one data analyzed in 2015 is presented in the results.

3.3 Changes of Physical and Chemical Properties in Pedosphere

Soil samples of three different SRC afforestation sites (SRC 2012, 2013 and 2014) were collected during the experimental period in 2013, 2014 and 2015, respectively and analyzed for pH, EC, organic matter, total nitrogen (T-N), available phosphorus (avail. P), sodium chloride content, texture, and exchangeable cations. The results are as follows (Table 6).

In general, reclaimed land in Korea has a high level of soluble salts and exchangeable sodium, which hinders the growth of the plants; however, this constraint may be reduced by the level of fertility [28]. The soil characteristics of the SRC in the Saemangeum land reclamation project area appear to be similar with those of the forest soil in terms of low salinity [13]. However, soil nutrients, total nitrogen (T–N), and available phosphorus (avail. P) were lower in the SRC soil than in the forest soil. In our results, organic matter, avail. P and T–N were the highest in SRC 2012 followed by 2013 and 2014 ($P \leq 0.05$), whereas the sodium chloride and CEC were more increased in SRC 2014 than others, but there are not significantly different. Based on this soil condition, we monitored annual pattern and pedosphere type by dividing moderate (13W, 14W) and low fertility (15D). The soil volumetric moisture content at 30cm below and soil temperature at 30 were investigated on three different SRC afforestation sites (SRC 2012, 2013 and 2014). At this site, the soil volumetric moisture content (%) at 30cm below and mean soil temperature (˚C) at 30cm below are approximately 28.5 % (maximum: 34 % minimum 21 %) and 15.3 °C (maximum: 30.1 °C, minimum 0.7 °C), respectively and the moisture content during the peak growing season (June–August) in 2013 (13W), 2014 (14W) and 2015 (15D) was 27.63, 30.26 and 27.17 %, respectively (Fig. 5). Based on this soil condition, we monitored seasonal and annual pattern by dividing wet or moderate condition (2013, 2014) and drought (2015).

Table 6. Soil condition (0-20 depth) of SRC established in Saemangeum reclaimed land throughout 2012, 2013 and 2014

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Sites	$pH_{(1:5)}$	$EC_{(1:5)}$ (dS m^{-1})	OM (%)	CEC (cmol kg^{-1})
2012	7.7	0.08	2.0^{a}	7.9^{a}
2013	7.4	0.10	1.16^{b}	7.89^{a}
2014	7.6	0.11	0.66^{c}	7.82^{a}

Sites	avail. P (mg kg^{-1})	T-N (%)	NaCl (%)	Texture
2012	16.5^{a}	0.16^{a}	0.005^{a}	SiL
2013	15.29^{ab}	0.06^{ab}	0.006^{a}	SiL
2014	13.19^{b}	0.04^{ab}	0.007^{a}	SiL

Sites	K	Na	Mg	Ca
		(cmol kg^{-1})		
2012	0.01	0.01	0.01	0.01
2013	0.01	0.01	0.01	0.01
2014	0.01	0.01	0.01	0.01

pH, potential of hydrogen. EC, electrical conductivity. OM, organic matter. avail. P, available phosphorus, T-N, total nitrogen, SiL, silt loam. All samples were collected in October 2013, 2014 and 2015, respectively, except for root biomass. One-way ANOVA test was performed to evaluate the differences among three sites (2012, 2013 and 2014). Post hoc comparisons were performed using the Tukey's post test at a significance level of $P \leq 0.05$. Different alphabetical letters in the same column (three sites) represent significant differences according to independent samples at $p \leq 0.05$.

3.4 Changes in the Flora Distribution of SRC and Neighboring Vegetation

The changes of flora distribution on the SRC in Saemangeum area were monitored for 3 years. Our result showed that the changes of dominant species and species composition in the SRC 2012, 2013, 2014, neighboring vegetation of SRC2012, 2013 and 2014, respectively (Tables 7, 8, 9). In site 2012, dominant species on first rotation and second rotation were *Aster subulatus* Michx. (glycophyte) and *Setaria viridis* (glycophyte), respectively. Moreover, dominant species on third rotation was also

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investigate *Setaria viridis* (glycophyte). The neighboring vegetation of site 2012 were dominant in *Phragmites communis* Trin (halophyte) for the three years (first, second and third rotation). Even if glycophyte was appeared on first rotation, dominant species was occupied with halophyte for three years. In SRC 2013, dominant species was only *Echinochloa crus-galli* (L.) P.Beauv. (glycophyte) on first rotation and second rotation also showed similar pattern, even if halophyte is appeared (16.67 %) on second rotation. The neighboring vegetation of site 2013 were dominated by both *Phragmites communis* Trin. (halophyte) and *Echinochloa crus-galli* var. *echinatum* (Willd.) Honda (glycophyte) on first year. However, the vegetation of second year is dominated by *Calamagrostis epigeios* (halophyte). In SRC 2014, afforested site most recently, *Echinochloa crus-galli* (L.) P.Beauv. and *Setaria viridis* (glycophyte) were appeared and dominant species is investigated with *Echinochloa crus-galli* (L.) P.Beauv. On the contrary, the neighboring vegetation of site 2014 has two glycophyte species (*Aster subulatus* var. *sandwicensis* and *Echinochloa crus-galli* var. *echinatum* (Willd.) Honda) and one halophyte species (*Calamagrostis epigeios*), but dominant species was glycophyte.

Table 7. Change of herbaceous vegetation of SRC established in 2012 in Saemangeum reclaimed land

Sites	RT (tree age)	Species	CL	DS*	F** (%)	RD*** (%)	n**** (EA ha^{-1})
SRC2012 [a]	13W[X] (1)	*Setaria viridis*			33.33	36.56	2,000
		Phragmites communis Trin.			13.33	16.13	800
		Echinochloa crus-galli (L.) P.Beauv.			6.67	8.60	400
		Aster subulatus Michx.*	glycophyte	+	46.67	38.71	2,800
	14W[Y] (2)	*Sonchus brachyotus*			20.00	16.67	1,200
		*Setaria viridis**	glycophyte	+	26.67	23.33	1,600
		Phragmites communis Trin.			20.00	22.22	1,200
		Panicum bisulcatum			13.33	15.56	800
		Calamagrostis epigeios			13.33	14.44	800
		Setaria faberi			6.67	7.78	400
	15D[Z] (3)	*Setaria viridis**	glycophyte	+	28.57	31.51	1,600
		Phragmites communis Trin.			21.43	17.81	1,200
		Panicum bisulcatum			7.14	6.85	400
		Calamagrostis epigeios			21.43	19.18	1,200
		Aster subulatus var. *sandwicensis*			21.43	24.66	1,200
NV2012[b]	13W[X] (1)	*Aster subulatus* Michx.	glycophyte		33.33	37.50	800
		Phragmites communis Trin.*	halophyte	+	66.67	62.50	1,600
	14W[Y] (2)	*Phragmites communis* Trin.*	halophyte	+	100.00	100.00	2,400
	15D[Z] (3)	*Phragmites communis* Trin.*	halophyte	+	100.00	100.00	1,200

RT, rotation of coppices; CL, classification. F (%) = [number of plots appeared specific species] × [number of total plot (5m × 5m) in field site]$^{-1}$ × 10^{2}. RD (%) = (number of specific plant species among all plot of specific site) × (number of total species appeared in all plot of specific site) $^{-1}$ × 10^{2}. n (EA ha^{-1})= [the number of specific plant species appeared in all plot of specific site] × [(the number of specific plant species appeared in all plot of specific site) × (the number of plots × plot area(5m × 5m)) $^{-1}$] $^{-1}$ × 10^{4}. *DS, dominant species, **F, frequency, ***RD, relative density, ****n = number of plants per ha. [a]plot of short-rotation coppice (SRC) established in 2012 (3-year-old seedlings; density, 1 × 1m), [b]plot of neighboring vegetation (NV) surrounding SRC established in 2012, "+" means dominant plant species in this site.

Table 8. Change of herbaceous vegetation of SRC established in 2013 in Saemangeum reclaimed land

Sites	RT (tree age)	Species	CL	DS[*]	F[**] (%)	RD[***] (%)	n[****] (EA ha^{-1})
SRC2013[a]	13W[X] (NA)	NA					
	14W[Y] (1)	*Echinochloa crus-galli* (L.) P.Beauv.[*]	glycophyte	+	100.00	100.00	2,400
	15D[Z] (2)	*Aster subulatus* var. *sandwicensis*[*]	glycophyte	+	66.67	68.75	1,600
		Setaria viridis	glycophyte		16.67	12.50	400
		Phragmites communis Trin.	halophyte		16.67	18.75	400
NV2013[b]	13W[X] (NA)	NA					
	14W[Y] (1)	*Phragmites communis* Trin.[*]	halophyte	+	33.33	37.50	400
		Echinochloa crus-galli var. *echinatum* (Willd.) Honda[*]	glycophyte	+	33.33	37.50	400
		Calamagrostis epigeios	halophyte		33.33	25.00	400
	15D[Z] (2)	*Aster subulatus* var. *sandwicensis*			33.33	33.33	400
		Echinochloa crus-galli var. *echinatum* (Willd.) Honda	glycophyte		33.33	27.78	400
		Calamagrostis epigeios[*]	halophyte	+	33.33	38.89	400

RT, rotation of coppices; CL, classification. F (%) = [number of plots appeared specific species] × [number of total plot (5m × 5m) in field site]$^{-1}$ × 10^2. RD (%) = (number of specific plant species among all plot of specific site) × (number of total species appeared in all plot of specific site) $^{-1}$ × 10^2. n (EA ha^{-1}) = [the number of specific plant species appeared in all plot of specific site] × [(the number of specific plant species appeared in all plot of specific site) × (the number of plots × plot area (5m × 5m)) $^{-1}$] $^{-1}$ × 10^4. [*]DS, dominant species, [**]F, frequency, [***]RD, relative density, [****]n = number of plants per ha. [a]plot of short-rotation coppice (SRC) established in 2013 (2-year-old seedlings; density, 1 × 1m), [b]plot of neighboring vegetation (NV) of SRC established in 2013. NA, no value has been established. "+" means dominant plant species in this site.

Table 9. Herbaceous vegetation of SRC established in 2014 in Saemangeum reclaimed land

Sites	RT (tree age)	Species	CL	DS[*]	F[**] (%)	RD[***] (%)	n[****] (EA ha^{-1})
SRC2014[a]	13W[X] (NA)	NA					
	14W[Y] (NA)	NA					
	15D[Z] (1)	*Echinochloa crus-galli* (L.) P.Beauv.[*]	glycophyte	+	77.78	78.26	2,800
		Setaria viridis	glycophyte		22.22	21.74	800

Sites	RT	Species	CL	DS	F	RD	n
NV2014[b]	13W^{X} (NA)	NA					
	14W^{Y} (NA)	NA					
	15D^{Z} (1)	*Aster subulatus* var. *sandwicensis*	glycophyte		33.33	23.81	40
		Calamagrostis epigeios	halophyte		33.33	33.33	40
		Echinochloa crus-galli var. *echinatum* (Willd.) Honda*	glycophyte	+	33.33	42.86	40

RT, rotation of coppices; CL, classification. F (%) = [number of plots appeared specific species] × [number of total plot (5m × 5m) in field site]$^{-1}$ × 10^2. RD (%) = (number of specific plant species among all plot of specific site) × (number of total species appeared in all plot of specific site) $^{-1}$ × 10^2. n = [the number of specific plant species appeared in all plot of specific site] × [(the number of specific plant species appeared in all plot of specific site) × (the number of plots × plot area (5m × 5m)) $^{-1}$] $^{-1}$ × 10^4. *DS, dominant species, **F, frequency, ***RD, relative density, ****n (EA ha^{-1}) = number of plants per ha. [a]plot of short-rotation coppice (SRC) established in 2014 (1-year-old seedlings; density, 1 × 1m), [b]plot of neighboring vegetation (NV) of SRC established in 2014. NA, no value has been established. "+" means dominant plant species in this site.

3.5 Changes of Chlorophyll and Carotenoid Content

The changes of chlorophyll and carotenoid content on the SRC in Saemangeum area were monitored for 3 years. Interestingly, our result showed that the changes of chlorophyll content are affected by soil moisture, fertility and occurrence of halophyte based on meteorological condition during the last three years. Total chlorophyll concentrations of poplar trees in SRC 2012 were highest in first rotation (13W), followed by third rotation (15D) and second (14W). The average value of total chlorophyll in SRC 2013 plot in June and August in first rotation (14W) was 0.99 ± 0.48 mg g^{-1} of fresh weight (FW) and 0.91 ± 0.08 mg g^{-1} of FW, respectively. Meanwhile, the total chlorophyll content in there in second rotation (15D) was 0.75 ± 0.19 mg g^{-1}of FW and 0.57 ± 0.17 mg g^{-1} of FW, respectively. The chlorophyll a/b ratio of poplar in the SRC 2012 in June and August was increased in second rotation (14W) (0.34 ± 0.02; 0.34 ± 0.02) compared with first rotation (13W) (0.01 ± 0.00; 0.01 ± 0.00), however this value was decreased in third rotation (15D) (0.01 ± 0.00; 0.29 ± 0.01). The carotenoid content in the SRC 2012 in June and August had similar pattern with total chlorophyll and a/b ratio (Table 10).

In 2013 SRC, the total chlorophyll, carotenoid content and a/b ratio were higher in second rotation (15D) than first rotation (14W). However, chlorophyll content (0.99 ± 0.48; 0.91 ± 0.08) was lower than measured value in 13W, 14W and 15D in SRC 2012.

<Table 10>

Table 10. Total chlorophyll and carotenoid contents and chlorophyll a/b ratio of poplar leaf grown in the short-rotation coppice in Saemangeum reclaimed land throughout 2012, 2013 and 2014

Sites	RT	Chl a (mg g^{-1} FW)		Chl b (mg g^{-1} FW)		Chl$_T$ (mg g^{-1} FW)		Chl a/b		Car (mg g^{-1} FW)	
		Jun.	Oct.	Jun.	Oct.	Jun	Oct.	Jun.	Oct.	Jun.	Oct.
2012[+]	13W^{X}	1.22	1.22	0.26	0.23	1.58	1.54	0.01	0.01	0.44	0.43
	(1)	±0.06^{Z}	±0.06	±0.14	±0.02	±0.08^{a**}	±0.12^{a***}	±0.00^{b**}	±0.00^{c**}	±0.02^{a**}	±0.03^{a**}
	14W^{Y}	0.01	0.01	0.36	0.36	1.22	1.02	0.34	0.34	0.14	0.16
	(2)	±0.00	±0.01	±0.02	±0.02	±0.48^{a}	±0.43^{b}	±0.02^{a}	±0.02^{a}	±0.03^{b}	±0.05^{b}

	15D^{Z} (3)	0.02 ±0.00	0.51 ±0.14	0.33 ±0.13	0.18 ±0.05	1.24 ±0.39^{aA}	0.70 ±0.19^{bA}	0.01 ±0.00^{bA}	0.29 ±0.01^{bA}	0.13 ±0.02^{bB}	0.13 ±0.01^{bA}
2013^{++}	13W (NA)						–				
	14W (1)	0.01 ±0.00	0.02 ±0.00	0.33 ±0.13	0.28 ±0.12	0.99 ±0.48^{a*}	0.91 ±0.08^{a**}	0.00 ±0.00^{a*}	0.01 ±0.00^{b*}	0.17 ±0.06^{a*}	0.19 ±0.01^{a*}
	15D (2)	0.01 ±0.00	0.62 ±0.30	0.19 ±0.04	0.15 ±0.05	0.75 ±0.19^{aA}	0.57 ±0.17^{bA}	0.01 ±0.00^{aA}	0.29 ±0.02^{aA}	0.13 ±0.03^{bB}	0.14 ±0.04^{bA}
2014^{+++}	13W (NA)						–				
	14W (NA)						–				
	15D (1)	0.02 ±0.00	0.43 ±0.10	0.21 ±0.03	0.14 ±0.04	0.85 ±0.12^{A*}	0.57 ±0.14^{A*}	0.01 ±0.00^{A*}	0.30 ±0.02^{A*}	0.20 ±0.01^{A*}	0.16 ±0.03^{A*}

RT, rotation of coppices. Chl a, chlorophyll a content of poplar leaves. Chl b, chlorophyll b content of poplar leaves. Chl_T, total chlorophyll content of poplar leaves. Chl a/b, chlorophyll a/b ratio of poplar leaves. Car, carotenoid content of poplar leaves. ^{Z}Mean ± SE(n=15). "–" means unsprouted and/or unafforested area; NA, no value has been established; ^{X}13W, collected data in first rotation with wet season in 2013; ^{Y}14W, collected data in second rotation with wet season in 2014; ^{Z}15D, collected data in third rotation with dry season in 2015. $^{+}$2012, plot of short-rotation coppice (SRC) established in 2012. $^{++}$2013, plot of short-rotation coppice (SRC) established in 2013. $^{+++}$2014, plot of short-rotation coppice (SRC) established in 2014. One-way ANOVA test was performed to evaluate the differences among three sites (2012, 2013 and 2014). Post hoc comparisons were performed using the Tukey's post test at a significance level of $P \leq 0.05$. Data analysis in 2013 SRC was done by independence t-test ($P \leq 0.05$). Different uppercase letters in the same column (three sites) represent significant differences among three SRC sites (pedospheric condition) of the same meteorological condition at $p \leq 0.05$, Different lowercase letters in the same column represent significant differences among different meteorological conditions (wet and drought of same site) of the same site, Asterisk in the same column represent significant differences among different meteorological conditions and pedospheric condition of the same poplar stand ages (1-year, first rotation), as determined by Tukey's post test. Total chlorophyll, chlorophyll a/b ratio and carotenoid content with less than two different rotation or climate factor were excluded from the statistical analysis.

4. Discussion

We found that biomass plantations have the potential to become a significant carbon-neutral source of renewable energy. Wood is regarded as an ideal composite that can be regenerated perpetually and is an important source material for industries [51]. Analysis of the organization of ingredients in wood is necessary to ensure that the wood can be efficiently used as an alternative for finite resources [52,53]. It is little known that unlike the development of paddy fields on reclaimed land, afforestation of reclaimed land has been conducted worldwide, despite the fact that, in general, plant species cannot survive on reclaimed land when the soil is still barren, Nevertheless, poplar is suitable for SRC planning for several reasons: (1) it can easily adapt to new environments, (2) it is characteristically fast growing, (3) with its wide rhizosphere and high transpiration capacity, it can cleanse the land from fertilizer contamination [54], and 4) its burgeoning rootlet development is favorable for absorbing moisture and nutrients [55]. Shin et al. [31] has reported that on Korean reclaimed land, biomass production of *Populus euramericana* clones is the highest among woody crop species. This study found that the biomass production of *P. euramericana* in the SRC (total area, 55.6 ha) in the Saemangeum area was 195.49 Mg; in addition, carbon storage and CO_2 absorption were calculated to be 89.92 Mg C and 329.71 Mg CO_2, respectively. In general, 50% of the carbon content of deciduous trees is reported to be contained in the main body (stem) [36,37,39], but we investigated

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the content in more detail. Consequently, we noted that the carbon content of poplar in the SRC is different from that at other sites but not lower than at forest sites (43%). Kim et al. [56] also reported the Carbon content of 2-year-old poplar in short rotation coppice grown riparian area is 47.1 %. Thus, it is required to quantize carbon coefficient in various land use pattern such as barren area for sustainable SRC management [57]. Based on our estimation on carbon sequestration, it is expected to perform a key role in Saemangeuem SRC for not only wood energy output but also carbon sink or shelterbelt near Yellow Sea of South Korea. Son et al. [58] reported that the carbon emission quantity on automotive sector is 2.4 $MgCO_2$ ha^{-1} yr^{-1} motor $vehicle^{-1}$ in South Korea. In our study, it was revealed that poplar planted on Saemangeum area can remove annual carbon emission by motor vehicles, efficiently. Many previous researches reported that lack of precipitation, abundant PPFD and high summer temperature affect decrease of biomass yield and physiological effect on woody plant [59].

The energy value grown in SRC on Saemangeum reclaimed land had proper criteria despite pedospheric condition was more barren and soil moisture content was changed due to temporally severe drought. Generally, *Quercus mongolica*, common wood species distributed in mountain forest of South Korea, has 19 MJ kg^{-1} –20 MJ kg^{-1} based on Forest wood resource [60]. Compare with mountain forest resource, our result (18.8 MJ kg^{-1} –19.4 MJ kg^{-1}) was very efficient to produce bioenergy based on SRC management on barren area and reserved land in huge reclamation. In addition, SRC management is very efficient to carbon storage in soil. Because aboveground biomass: below ground biomass ratio is increased with aboveground biomass of stand well grown. It means belowground biomass can be decreased by 14–21 % compare with aboveground [60–62]. In other words, it is possible to maintain soil carbon sequestration with SRC management more easily than forest ecosystems. However, it will be required to investigate the effect of short rotation forest on soil carbon sequestration, and belowground biomass of fast growing tree.

Interestingly, the net height growth of poplar seedlings is rapidly increased in second rotation (14W) compared with first rotation (13W), but that of seedlings in third rotation (15D) was significantly decreased (Fig. 6) ($P \leq 0.05$). Based on volumetric soil moisture content, we classified climatic condition into two types (moderate (13W, 14W) and drought (15D)). Changes in tree volume are often inferred from DBH and tree height increment, which can have important implications for the accuracy of predictions [63]. Increment is more physiologically related to size than chronological age [64]. On top of that, height increment is more dependent on differences in genetics and environmental conditions, while diameter increment is more closely related to current amount of foliage and tree competitive status [65]. In this study, chlorophyll and carotenoid contents of poplar were sensitive to recent drought in SRC. Moreover, important changes are observed for chlorophyll a/b ratio under drought (15D) with decrease of the ratio in order to enhance photosynthetic efficiency against photo-inhibition [66]. In general, a/b ratio is reduced over 65 % in stress condition, because of contributing to the enlargement of the PS II antenna size, enhancing chlorophyll b contents [67]. In many studies, reduced photosynthetic pigments were adaption of plant to protect from photo-inhibition and photodynamic damage in response to the drought [68, 69].

Kim et al. [15] reported that distribution of glycophyte (82.6 %, 95 species) is higher than that of halophyte (17.4 %, 20 species) in Saemangeum reclaimed land. Moreover, we explored flora distribution on SRC and its neighboring vegetation through 2013, 2014 and 2015. The Saemangeum area has been transformed into a different environment from the existing tidal flat ecosystem due to reclamation. Generally, *Phragmites communis* Trin. (halophyte) and other herbaceous plants grown in tidal flat are dominant in the reclaimed land in South Korea [70], but other dominant plants might be formed in the understory vegetation formed after afforestation the short rotation coppices, because of the shade effect [13]. In SRC 2012, dominant species was changed gradually in second and third rotation, and neighboring vegetation of SRC was also changed. Initially, *Aster subulatus* Michx. was dominant species on first rotation (13W), and species composition was changed by *Setaria viridis*. Kim [71] reported that indicator herbaceous plant in reclaimed land is divided 45 plants normally. Initial stage of reclamation, *Suaeda japonica* has achieved a dominant position as a pioneer halophyte, because it usually lives in pedosphere with T-N (0.22–0.31) and P_2O_5 (0.056–0.076) with high salinity

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(Na 7.22–7.36; Cl 9.27–10.90). *Aster subulatus* Michx, the species found in our site, usually lives in pedosphere with T-N (0.69–1.02) and P_2O_5 (0.074) with mid salinity (Na 1.98; Cl 2.37). In addition, *Phragmites communis* Trin., known as halophyte, lives in T-N (0.47–0.53) and P_2O_5 (0.039–0.041) with mid salinity (Na 0.41–0.71; Cl 0.47–1.35). It was found that halophyte distribution in SRC can be interpreted resalinization temporarily, but more long-term monitoring and additional studies will be required to predict precisely.

Once the drymass, as raw materials for producing fuel pellets, was combusted, its mineral ash remains in oxidized form. Ash content and its chemical composition affect the smooth operation of gasifiers. During the gasification process, the ash contents fuse and their cohesion forms a mineral residue. No mineral debris is left if the ash content in the biomass is less than 5% [72]. An ash content of 0.7% is considered first grade, of 1.5% is considered second grade, and of less than 3.0% is considered third grade [43]. Compared with the Pellet Fuel Institute standard in the USA and the EU's EN-Plus standard, the specifications in the Korean wood pellet standard eliminate the disadvantages in the assessment criteria of both (Table 9). In this study, the quality of poplar for wood pellet production was evaluated to be first to third grade, indicating that wood pellets can be manufactured and produced profitably from poplar grown in the Saemangeum SRC. Based on these results, we concluded that poplar grown in the Saemangeum land reclamation project area is not only useful for its biomass and energy production but also suitable to be carbon sink for GHG mitigation.

<Table 9>

Monitoring the plant diversity in the area surrounding the SRC showed that the dominant species in the Saemangeum land reclamation area had changed over three years. In 2013, the dominant species in the SRC was identified to be *S. viridis*, but *Sonchus brachyotus* and *C. epigeios* also increased in 2014 (second rotation of the SRC). Overall, poplar afforestation on reclaimed land changed the plant diversity. Oh and Choi [73] have reported that in reclaimed land, the occurrence of *C. epigeios* and *Sonchus brachyotus* is an intermediate step between desalination and vegetational succession. The influence of plant succession on the distribution of *S. viridis*, *Sonchus brachyotus*, and *C. epigeios* may be related to desalinization of the soil of reclaimed land. The change in the plant communities in the Saemangeum area appeared to be affected by the degree of desalination of the reclaimed soil. Moreover, our results showed that the low level of salinity in the soil was related to the progress in vegetational succession from reclaimed land to short-rotation forest in the Saemangeum area.

5. Conclusions

Our study has two significant findings for short rotation coppice in Saemangeum reclaimed land. Firstly, in this study, *P. euramericana* in the SRC of the Saemangeum land reclamation area has huge potential for GHG mitigation via carbon storage and for yielding biomass to produce raw material for generating bioenergy. Furthermore, *P. euramericana* grown this area scored third grade (G3) in the Korean wood pellet specification, indicating that *P. euramericana* grown here can contribute to the sustainable production of bioenergy. The biomass yield per area of poplar grown was calculated to be 13.5 oven dry tons ha^{-1} $year^{-1}$, and the carbon stock and CO_2 absorption volume were estimated to be 6.2 Mg C ha^{-1} $year^{-1}$ and 22.9 Mg CO_2 ha^{-1} $year^{-1}$, respectively. Nevertheless, future studies are clearly needed to further understand effects of long-term monitoring on carbon storage potential, such as scenario analysis, growth pattern and carbon storage of belowground and aboveground of *Populus* in Saemangeum area. Second, in terms of microclimate, this is the only study quantifying the amount of flora distribution in costal reclaimed SRC during drought, especially in Saemangeum area. Our findings suggest that halophyte distribution and soil nutrient in afforested area of reclaimed land can be changed during drought, being changed its soil moisture condition. Although the total biomass production and carbon sequestration is valuable for SRC management, sustainable management will be also strongly required to operate domestic bioenergy production and carbon credit as appears by decrease of net growth and photosynthetic pigment of poplar seedlings. Therefore, sustainable management, yield modeling, and long-term monitoring of the Saemangeum SRC are needed to mitigate GHGs. In addition, these results suggest that current short

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rotation forest management in marginal areas, such as the Saemangeum land reclamation project area, should be steadily monitored to minimize the decline in afforested areas by restoring the vegetation of reclaimed land, monitoring vegetation succession.

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