forests

MDPI

Article

The Evaluation of Radiation Use Efficiency and Leaf Area Index Development for the Estimation of Biomass Accumulation in Short Rotation Poplar and Annual Field Crops

Abhishek Mani Tripathi [1,*], Eva Pohanková [1,2], Milan Fischer [1,2], Matěj Orság [1,2], Miroslav Trnka [1,2], Karel Klem [1] and Michal V. Marek [1]

1 Global Change Research Institute CAS, Bělidla 986/4a, 603 00 Brno, Czech Republic; eva.pohankova@seznam.cz (E.P.); fischer.milan@gmail.com (M.F.); orsag.matej@gmail.com (M.O.); mirek_trnka@yahoo.com (M.T.); klem.k@czechglobe.cz (K.K.); marek.mv@czechglobe.cz (M.V.M.)

2 Department of Agrosystems and Bioclimatology, Faculty of Agronomy, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic

* Correspondence: manicfre@gmail.com or tripathi.a@czechglobe.cz; Tel.: +420-511-192-215

Received: 15 February 2018; Accepted: 23 March 2018; Published: 27 March 2018

Abstract: We evaluated the long-term pattern of leaf area index (LAI) dynamics and radiation use efficiency (RUE) in short rotation poplar in uncoppice (single stem) and coppice (multi-stem) plantations, and compared them to annual field crops (AFCs) as an alternative for bioenergy production while being more sensitive to weather fluctuation and climate change. The aim of this study was to evaluate the potential of LAI and RUE as indicators for bioenergy production and indicators of response to changing environmental conditions. For this study, we selected poplar clone J-105 (*Populus nigra* L. × *P. maximowiczii* A. Henry) and AFCs such as barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and oilseed rape (*Brassica napus* L.), and compared their aboveground dry mass (AGDM) production in relation to their LAI development and RUE. The results of the study showed the long-term maximum LAI (LAI_{max}) to be 9.5 in coppice poplar when compared to AFCs, where LAI_{max} did not exceed the value 6. The RUE varied between 1.02 and 1.48 g MJ^{-1} in short rotation poplar and between 0.72 and 2.06 g MJ^{-1} in AFCs. We found both LAI and RUE contributed to AGDM production in short rotation poplar and RUE only contributed in AFCs. The study confirms that RUE may be considered an AGDM predictor of short rotation poplar and AFCs. This may be utilized for empirical estimates of yields and also contribute to improve the models of short rotation poplar and AFCs for the precise prediction of biomass accumulation in different environmental conditions.

Keywords: aboveground biomass; bioenergy; leaf area index; *Populus*

1. Introduction

IPCC [1] reported that the energy security and mitigation of greenhouse gas emissions are major challenges to meet global energy demand. Moreover, the entire food system is considered as a source of greenhouse gas emissions and primary production is by far the most important component [2]. To reduce greenhouse gas emissions, mitigate climate change impacts and, at the same time, fulfill the requirements of food and energy demands, it is important to enhance the sources of biomass production in the short term such as short rotation forestry (SRF) and bioenergy feedstocks (woody and non-woody) [3,4].

However, incentives are needed to persuade crop and livestock producers, agro-industries, and ecosystem managers to adopt good practices for mitigating climate change and improving the productivity of crops in different environmental conditions [5]. The cultivation of biomass, mainly poplars (*Populus*) and willows (*Salix*) in SRF, particularly in coppice management, also known as short rotation coppice (SRC), has considerable potential to meet these requirements. Besides being a production source of biomass for bioenergy, SRC can contribute to the improvement of ecosystem services such as increasing biodiversity, reducing soil erosion, improving water use efficiency, phytoremediation, and reducing greenhouse gas emissions [6,7]. Moreover, in some regions, AFCs also represent an alternative solution for biomass and bioenergy production [8,9]. The suitability of the species for bioenergy production can vary with local soil and climatic conditions and may also show differences due to their sensitivity to changing environmental conditions in the context of climate change.

For this reason, indicators that would make easier comparison of species differences and the responses to climate change in aboveground dry mass (AGDM) production are of high interest. The cultivation of biomass under field conditions depends on the productivity and growth of the species. The variation in productivity and growth is closely linked to the amount of intercepted radiation, largely determined by leaf area index (LAI) [10] which is defined as the one sided green leaf area per unit ground surface area [11], the interception of photosynthetically active radiation (PAR; 400–700 nm), and by interactions with numerous environmental factors and physiological characteristics [12,13].

An intercepted PAR depends mainly on the plant's LAI, canopy architecture (affecting how much LAI is effectively exposed to light), and the physiological capacity to intercept radiation. Thus, plant growth and productivity under field conditions are primarily dependent on the potential of the canopy to intercept incoming PAR and to convert it into biomass [14,15].

The amount of biomass produced per unit of intercepted light is called radiation use efficiency (RUE) and largely determines the growth and biomass in both woody (trees) and non-woody (AFCs) plants [16–18]. Monteith [12] defined the concept of RUE as the ratio between the quantity of dry mass (DM) production and the quantity of accumulated intercepted PAR (IPAR).

In numerous studies, a linear relationship between IPAR, RUE, LAI, leaf area duration (LAD), and biomass production has been found in bioenergy feedstocks and AFCs such as poplar, willow, barley, wheat, maize, and oilseed rape [13,19–21]. The actual RUE and LAI are affected by several factors such as environmental conditions (temperature, water, and nutrient availability [22,23]), phenology, and LAD [24,25].

The RUE also varies in different vegetation types for example in woody and herbaceous plants or management type such as coppiced and uncoppiced, as well as plant density and growth rate [26–31]. Usually, RUE values are higher in AFCs compared to fast growing woody plantations. On the other hand, in most studies the maximum LAI (LAI_{max}) is higher in woody plants [32–34].

To evaluate the contribution of RUE and LAI to AGDM accumulation, several studies on bioenergy feedstocks in different regions were conducted. However, the understanding of these relationships is still low and particularly the knowledge of the differences between plant species are needed to improve bioenergy feedstock growth and production analysis [35–40].

In the present study, we evaluated the dynamics of LAI, LAD, RUE, and AGDM for the growth of poplar clone J-105 (*Populus nigra* L. × *P. maximowiczii* A. Henry) in a high-density short rotation (coppiced and uncoppiced management) on former arable land, AFCs-spring barley (SB, *Hordeum vulgare* L.), winter wheat (WW, *Triticum aestivum* L.), silage maize (SM, *Zea mays* L.), and oilseed rape (OR, *Brassica napus* L.).

We hypothesized the role of RUE and LAI development in determining AGDM production. The aims of this study were: (1) to determine the variation of LAI development, LAD, and RUE between SRC poplar and AFCs; (2) to investigate the relationship between LAI, LAD, RUE, and AGDM in SRC poplar and AFCs as this may help to understand differences in AGDM production in different plant types and species, thus, improving the forecasting of the productivity of SRC poplar and AFCs.

2. Materials and Methods

2.1. Site Description and Treatments

The experiment was conducted in a Domanínek research site (the Czech Republic 49°31′ N, 16°14′ E; 530 m a.s.l.). The research site is located on a slight slope of 3–5° with an eastern aspect and characterized by a temperate climate which is typical for this part of Central Europe with mingling continental and maritime influences [41,42].

The long-term (2002–2014) total annual amount of precipitation and mean annual air temperature at the research site was 603 mm and 7.6 °C, respectively. The area is relatively dry due to low annual precipitation; however, the experimental site is appropriate for SRC and AFCs cultivation due to a deep soil profile with optimum water holding capacity [41]. The soil type is luvic cambisol, influenced by gleyic processes [41] and the texture vary from silt loam (0–0.3 m) to loam (0.3–2.0 m). The soil sampling was carried out prior to planting the poplar clone J-105 and sowing SB, WW, SM, and OR, respectively. The basic soil characteristic such as the total nitrogen (N), organic matter, soil type, bulk density, soil pH, and available nutrients are shown in Table 1.

Table 1. The selected soil characteristics of the experimental site taken from Trnka et al. [41].

Soil Characteristics	Units	Depth (cm)			
		0–24	24–66	66–94	94–130+
Silt	wt %	50	46.1	38.7	19.6
Clay	wt %	15.8	26.3	18.6	13.3
Bulk density	g/cm^3	1.55	1.64	1.59	1.64
Organic matter	wt %	2.65	0.28	0.14	0.14
Total nitrogen	wt %	0.16	<0.05	<0.05	<0.05
pH (KCl)		5.9	5.4	4	3.4
Available P	mg/kg	148	1.3	0.9	24
Available K	mg/kg	15	91	62	76
Available Mg	mg/kg	143	230	278	291
Available Ca	mg/kg	1230	1353	748	652

The poplar clone J-105 plantation of 2.85 ha was established in April 2002 on former arable land. Hardwood cuttings were planted in a double-row design with spacing of 0.7 m within the rows and inter-row distances of 2.5 m, resulting in a density 9216 trees ha^{-1}. Irrigation, fertilizers, or pesticides were not applied before or after planting. The measurements were conducted during two consecutive rotations. The first rotation spanned from 2002–2009 (uncoppiced-single stem stand) and the second rotation from 2010–2015 (coppiced-multi stem stand). The single stem stand was cut 10–15 cm above the ground level in 2009 (total age of trees from planting to harvest was eight years) and subsequently in 2010 the multi stem stand coppice culture was established. AFCs were sown in close distance (ca. 500 m to 1 km) to woody poplar plantation. These crops were cultivated between 2011 and 2013 with two cultivars for SB (Tolar-SB-T and Bojos-SB-B) and one cultivar for WW (Etela-WW-E), SM (MON3301-SM-M), and OR (Rohan-OR-R), respectively. The experimental designs for all AFCs were identical for all the years (2011–2013). These AFCs were established on standardized 12 m^2 (1.5 × 8 m) plots and each AFC was cultivated in three replicates (A, B, and C) for measurements [43]. The AFCs were sown with appropriate seeding rates for given conditions and during the sowing, the AFCs nitrogen (N) fertilizer was applied with optimum doses (see Table 2).

Table 2. The sowing of non-woody annual field crops (AFCs) spring barley (SB), winter wheat (WW), silage maize (SM), and oilseed rape (OR), and the fertilizer (Nitrogen—N) rate in different growing seasons.

Annual Field Crops (AFCs)	Cultivars	Sowing Date	Seeding Rate (kg ha^{-1})	N Rate (kg ha^{-1})
Spring barley	Tolar	11 April 2011	220	60
Spring barley	Tolar	17 April 2012	220	70
Spring barley	Bojos	18 April 2013	220	30
Spring barley	Bojos	12 March 2014	220	30
Winter wheat	Etela	4 October 2011	200	15
Winter wheat	Etela	26 September 2012	200	15
Silage maize	MON3301	10 May 2012	35	140
Oilseed rape	Rohan	16 August 2011	4.5	60

2.2. Field Measurements and Data Collection

All measurements (meteorological, LAI, AGDM production, IPAR, and RUE) were carried out for SRC poplar clone J-105 (for uncoppiced in growing seasons 7–8 and for coppiced-growing seasons 1–4), and AFCs. The data sampling dates covered all stages of canopy development, from the beginning of the growing season (leaf flushing) to the end of the growing season (completely fallen leaves) in SRC poplar and crop emergence to ripening (before harvesting) in AFCs.

2.3. Meteorological Measurements

Meteorological data (air temperature, incident global radiation, and precipitation) were recorded continuously by an automatic weather station placed at the turf grass close (~15–20 m) to the SRC poplar plantation [42]. The used instruments consist of combined air temperature/relative humidity sensor EMS 33 (EMS Brno, Brno, the Czech Republic), precipitation tipping bucket rain gauge MetOne 370 (MetOne Instruments, Grants Pass, OR, USA), and global radiation sensors EMS 11 (EMS Brno, Brno, the Czech Republic), respectively. The PAR was calculated as 0.5 of the global radiation [44]. The weather conditions during the measurement period for seven years from 2008–2014 are presented in Figure 1. The mean annual air temperature (in °C) was within the range of normal conditions. The annual precipitation was almost the same (ranging from 511–554 mm) between all the years except 2009 and 2010 when the total precipitation was higher, with the highest reported in 2009. The annual incident global radiation for each growing season (from April–October, for all measurement years) varied between 2971.28–3247.03 MJ m^{-2}, however, a slightly lower value was observed in 2010 (see Figure 1B).

2.4. Leaf Area Development Measurements

In situ LAI measurement methods can be grouped into two main categories such as direct (destructive and non-destructive) and indirect (non-destructive). Indirect non-destructive LAI measurement methods involve several approaches with advantages and disadvantages for different types of vegetation [45,46]. The LAI development was evaluated throughout each of the growing season in SRC poplar and AFCs. The LAI was indirectly measured by a SunScan plant canopy analyzer (Delta-T Devices, Cambridge, UK). For SRC poplar, the LAI was measured at three different places between rows and within rows while for AFCs, the LAI was measured in each individual replicate. The LAI measurements were repeated weekly and biweekly in the same measurement points. This indirect LAI method was validated because first time SunScan was used in woody SRC poplar plantation/referenced ($r^2 = 0.82$, $y = 1.05 - 0.7$, $p < 0.001$) for SRC poplar [47], and for AFCs it followed the calibration from earlier studies in different crops such as soybean, maize, and wheat [48–51]. For daily LAI, the weekly and biweekly LAI data were interpolated using a regression equation with the cumulative mean daily air temperature sum (>5 °C) [52]. The LAI$_{max}$ (during the peak of growing period), LAI$_{mean}$ (the mean of the LAI, during the growing period), ∑LAI (the sum of the daily LAI during the growing period), and LAD (the count of the total number of days from bud burst to completely fallen leaves to the ground) was evaluated for each growing season in SRC poplar and AFCs, respectively.

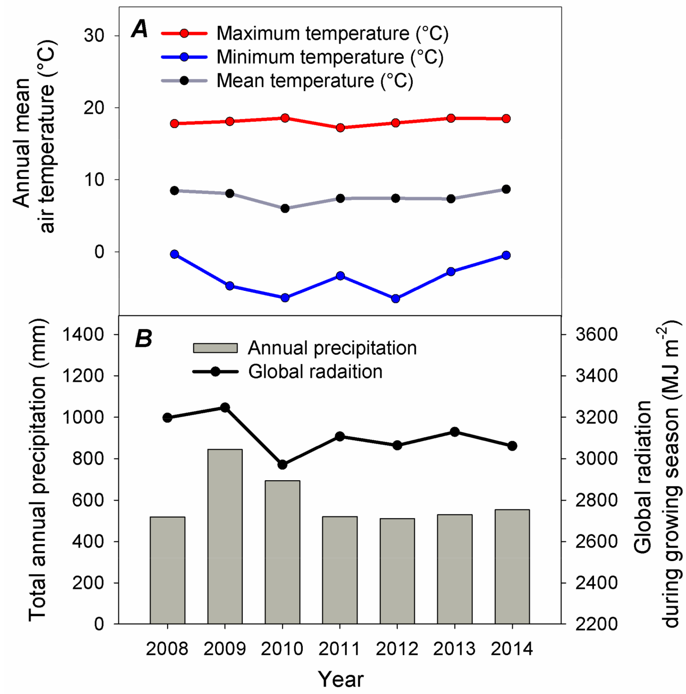

Figure 1. (**A**) The air temperature (°C; maximum, minimum, and mean) and (**B**) the total amount of annual precipitation (mm) and the total sum of incident global radiation (MJ m^{-2}) per growing season (April–October) from 2008–2014 at the research site Domanínek, Czech Republic.

2.5. Aboveground Dry Mass (AGDM) Production Estimation

In uncoppiced poplar, the AGDM was estimated for the seven and eight growing season using an allometric equation which was developed by Fischer et al. [53]. However, for the coppiced plantation, we developed a specific allometric equation using the methodology suggested by Fischer et al. [53]. In winter 2011 (after two years of coppiced growth), 25 trees were randomly selected in the range of 10–40 mm diameter at breast height (DBH, 130 cm above the ground level) and trees were harvested 10–15 cm above the ground level. The DBHs of the tree were measured by using a digital caliper (150 mm digital caliper DC04150, Digital Micrometers Ltd., Sheffield, UK). The whole tree was divided into two parts, stem and branches for chipping, in order to determine the woody dry mass (DM). The chipping samples were stored in aluminum boxes and subsequently dried in an oven at 105 °C until constant weight was achieved [54,55]. The amounts taken on the collected material were used to correlate DBH with the dry weights, and to develop a non-linear (power function) allometric Equation (1) (Figure S1) for the coppiced poplar.

$$\mathrm{DM} = \mathrm{a.DBH}^{\mathrm{b}} \tag{1}$$

where DM is dry mass, a and b are specific regression coefficients, and DBH is the diameter of the trees at breast height.

The AGDM in SRC poplar was estimated from the DBH inventory of the winter habitus of trees at the end of each growing season and followed by using allometric equation (Figure S1). In AFCs, the AGDM was estimated at least six times during the growing season using a regular harvesting method. For determining the dry matter production, we harvested aboveground biomass of AFCs and dried them until constant weight. For AGDMs, dry matter content was determined per m^2 and scaled up per ha (10,000 m^2). This methodology was followed due to a recommendation for variety testing of the State Institute for Agriculture Supervision and Testing with daily monitoring of weather parameters through automated weather station and daily collection of experimental information through regular oversight by experienced experimenter and technicians [43].

2.6. The Evaluation of Intercepted Photosynthetic Active Radiation (IPAR) and Radiation Use Efficiency (RUE)

In the SRC poplar clone J-105 and AFCs, the RUEs were calculated (see Equation (2)) from the ratio between the produced AGDM (g DM m^{-2}) and the total amount of accumulated IPAR (MJ m^{-2}) during each growing season.

$$\mathrm{RUE} = \mathrm{W_s}/\mathrm{IPAR} \quad (2)$$

where W_s = total AGDM production (g DM m^{-2}) and the IPAR was evaluated using Lambert-Beer's Law function [56]:

$$\mathrm{IPAR} = \mathrm{PAR_{above}}\,(1 - e^{-k\mathrm{LAI}}) \quad (3)$$

where PAR_{above} represents the cumulated PAR above the canopy and k represents the light extinction coefficient. For fast growing trees k is estimated to vary between 0.4–0.6 [52] while in the case of AFCs such as barley and wheat, k ranges between 0.4 and 0.5, respectively [49,50,57].

In the present study, we calculated k for the poplar clone J-105, SB, WW, SM, and RS, respectively using Equation (4) [58]

$$k = -\ln\,(\mathrm{PAR_t}/\mathrm{PAR_i})/\mathrm{LAI} \quad (4)$$

where PARt is the transmitted PAR (below the canopy), PAR_i is the incoming PAR (above the canopy), and LAI is the leaf area index.

2.7. Statistical Analysis

The power function of the allometric equation between the AGDM and DBH [59] and the linear regression among the studied variables (LAI_{max}, LAD, RUE, and AGDM) of SRC poplar [28] and AFCs were fitted in SigmaPlot® version 11.0 (Systat Software, San Jose, CA, USA). Pearson's correlation coefficients were estimated using the same software for individual relationships.

3. Results

3.1. Leaf Area Development

The time course of LAI for SRC poplar (uncoppiced-PU and coppiced-PC) and for AFCs is shown in Figure 2A–C.

The LAI dynamics changed in SRC poplar (PU and PC) particularly with the development of the canopy and management. In AFCs (SB-T, SB-B, WW-E, SM-M, and OR-R) the LAI dynamics varied mainly due to crop characteristics and also in response to the growing season (Figure 2). The LAI_{max} varied between 3.6–9.5 m^2 m^{-2} in SRC poplar, 3.1–5.6 in SB, 4.1–6.0 m^2 m^{-2} in WW, and reached values of 3.5 in SM and 5.6 m^2 m^{-2} in OR.

In AFCs, the highest measured LAI_{max} was 6.0 m^2 m^{-2} in WW but the LAI_{max} and also the LAI development dynamics varied between the growing seasons (Figure 3).

Besides LAI development, LAD, which is an important parameter to define the plant productivity and is interconnected to LAI development and RUE, was also studied. The LAD for SRC poplar and AFCs is shown in Figure 3. The maximum LAD (186 days) was found in SRC poplar in 2009 (after eight years of plant growth in uncoppiced management) and the minimum LAD (68 days) was observed in SM.

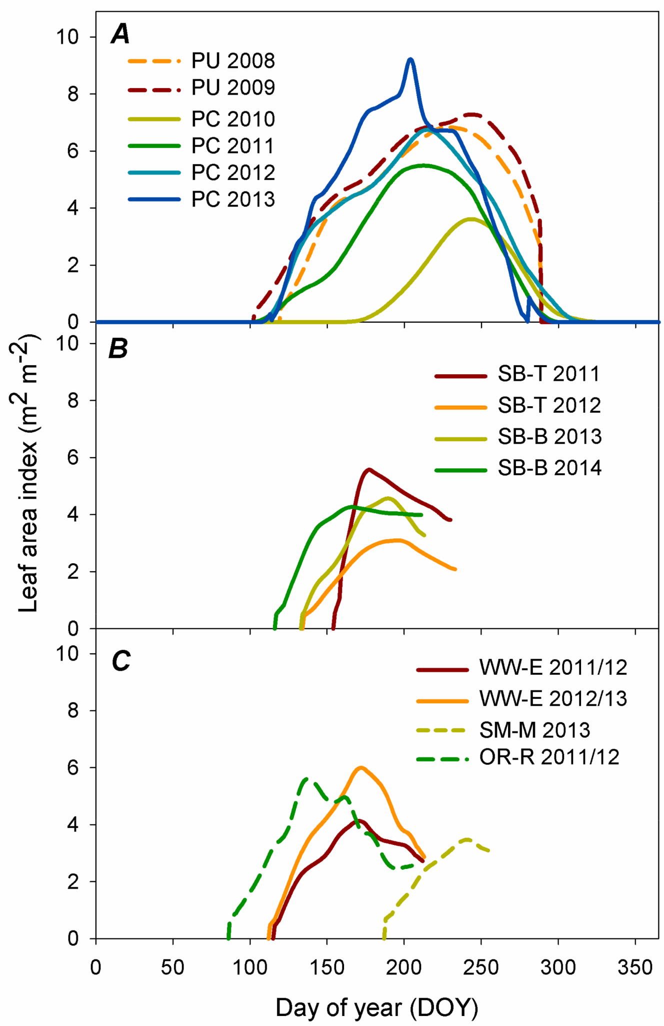

Figure 2. The time course of leaf area index (LAI) in SRC poplar clone J-105 (**A**) uncoppiced (PU) from 2008–2009 and coppiced (PC) from 2010–2013; the time course of LAI in AFCs (**B**) spring barley cultivar Tolar (SB-T) from 2011–2012 and cultivar Bojos (SB-B) from 2013–2014; and (**C**) winter wheat cultivar Etela (WW-E) from 2011/2012–2012/2013, silage maize cultivar MON3301 (SM-M) in 2013, and oilseed rape cultivar Rohan (OR-R) in 2011/12.

3.2. Radiation Use Efficiency (RUE)

RUE is another main determinant of biomass production in SRC plants and AFCs. For the poplar clone J-105, the average RUE was 1.19 g MJ^{-1} over all six years. The maximum RUE was 1.48 g MJ^{-1} in PU 2009 (the last year of uncoppiced poplar cultivation) and the minimum RUE was 1.02 g MJ^{-1} in PC 2010 (the first year of coppiced poplar cultivation). The average RUE for AFCs was 1.57 g MJ^{-1} among all crops, years, and genotypes. The maximum RUE (2.06 g MJ^{-1}) was observed in AFCs SB (cultivar Bojos) in 2013 (SB-B 2013) and the minimum RUE (0.72 g MJ^{-1}) was observed in OR cultivated in 2011/2012 (Figure 3).

3.3. Aboveground Dry Mass (AGDM) Production

The AGDM production in SRC poplar clone J-105 varied from 3.6–16.5 t ha^{-1} $year^{-1}$ in different growing seasons (Figure 3). In the long term six-year observation, the mean AGDM production was estimated to be 10.5 t ha^{-1} $year^{-1}$ including PU and PC. The maximum AGDM production was observed in the last year of PU cultivation (2009) and the minimum AGDM production was observed in the first year of PC cultivation. It is evident that these differences are attributed particularly to the canopy development.

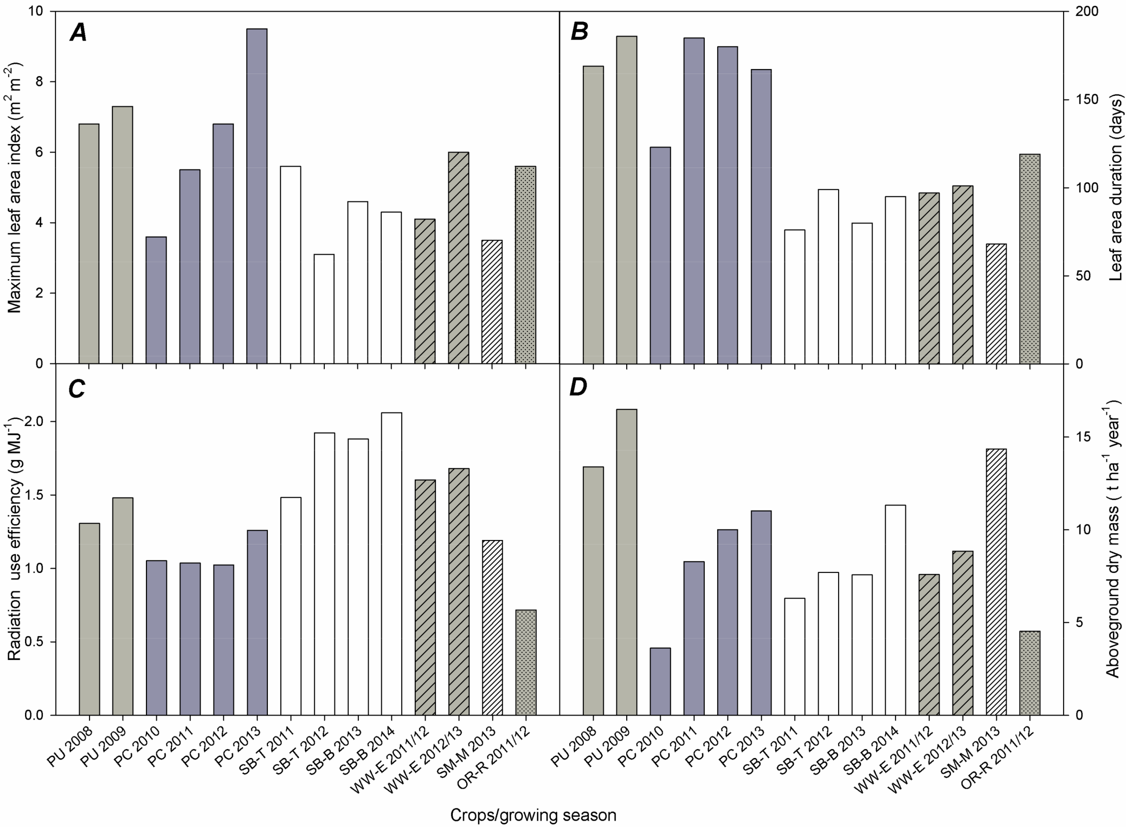

Figure 3. Comparison of (**A**) the maximum leaf area index (LAI_{max}, $m^2\ m^{-2}$); (**B**) the leaf area duration (LAD, days); (**C**) the radiation use efficiency (RUE, $g\ MJ^{-1}$); and (**D**) the aboveground dry mass (AGDM, $t\ ha^{-1}\ year^{-1}$) in SRC poplar clone J-105 uncoppiced (PU) from 2008–2009 and coppiced (PC) from 2010–2013 and AFCs (spring barley cultivar Tolar (SB-T) from 2011–2012 and cultivar Bojos (SB-B) from 2013–2014, winter wheat cultivar Etela (WW-E) from 2011/2012–2012/2013, silage maize cultivar MON3301 (SM-M) in 2013, and oilseed rape cultivar Rohan (OR-R) in 2011/2012).

The AGDM production in AFCs varied between 4.5 and 14.4 t ha^{-1} $year^{-1}$ and the average AGDM was 8.5 t ha^{-1} $year^{-1}$. The maximum AGDM was observed in SM-M (14.4 t ha^{-1} $year^{-1}$) and the minimum was observed in OR-R (4.5 t ha^{-1} $year^{-1}$) (Figure 3D). These observed differences can be related to RUE, sowing density, crop physiology, and N application.

3.4. Determinants of Aboveground Dry Mass (AGDM) Production in SRC Poplar and AFCs

The AGDM production showed a positive linear regression with LAI_{max}, LAI_{mean}, $\sum LAI$, LAD, and $\sum(LAI \times IPAR)$ in only SRC poplar, while a negative linear relationship was observed in AFCs (Figure 4A–D,F, respectively). For SRC poplar, a strong positive (R^2 values varied between 0.86 and 0.94) and linear relationships between AGDM production and LAI (LAI_{mean} and $\sum LAI$) or $\sum(LAI \times IPAR)$ were found. Using $\sum LAI$ (R^2 = 0.91) and $\sum(LAI \times IPAR)$ (R^2 = 0.94) improved the relationship to AGDM production compared to LAI_{mean} (R^2 = 0.86) and particularly to LAI_{max} (R^2 = 0.46) and thus, provided a better estimator of biomass production.

In SRC poplar and AFCs (excluding SM), the AGDM production was strongly (R^2 ranged from 0.70–0.72) and positively correlated to RUE (Figure 4E). Thus, the use of RUE provided a good estimation of AGDM production for both SRC poplar and AFCs, however, the relationship for AFCs was significantly improved if the C_4 crop SM was excluded from the dataset (R^2 = 0.7). The C_4 crop SM AGDM response to RUE fits better in the AGDM versus RUE relationship for SRC poplar.

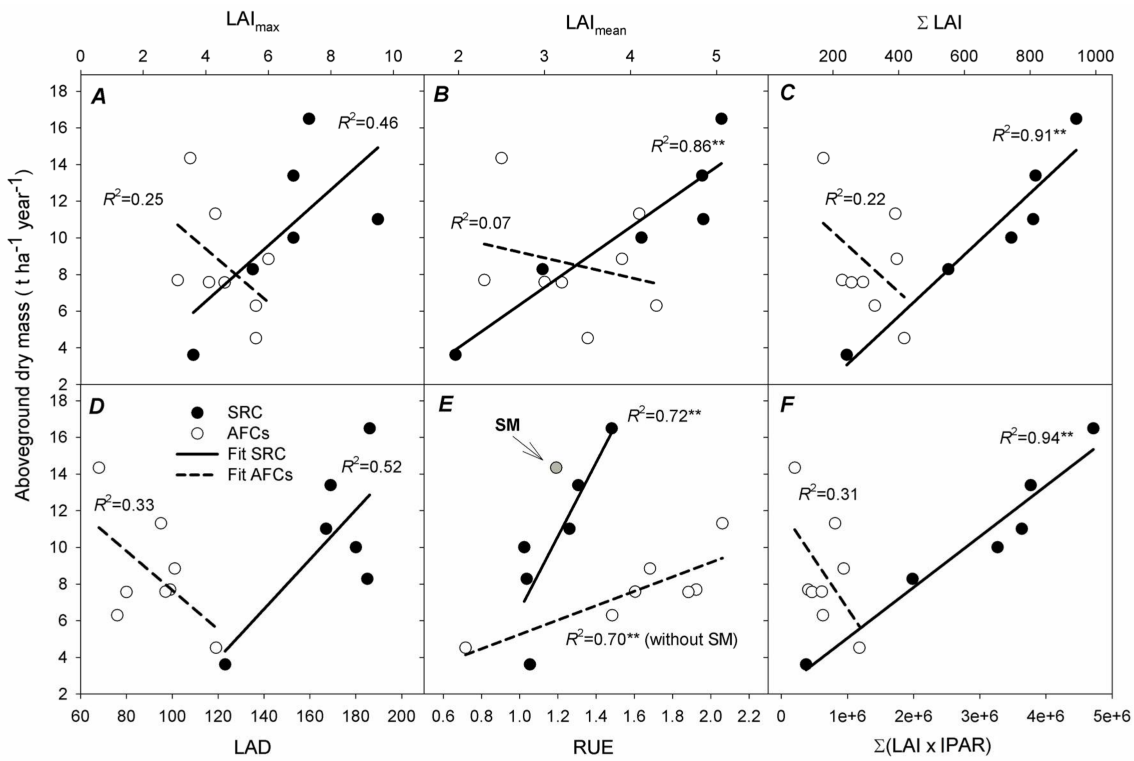

Figure 4. The relationships between aboveground dry mass (AGDM) production and: (**A**) the maximum leaf area index (LAI_{max}); (**B**) the mean LAI (LAI_{mean}); (**C**) the sum of LAI ($\sum$LAI); (**D**) the leaf area duration (LAD); (**E**) the radiation use efficiency (RUE); and (**F**) $\sum$(LAI $\times$ IPAR) (absorbed photosynthetically active radiation) in SRC poplar clone J-105 and AFCs, respectively. Note: ** significant Pearson correlation coefficients at 0.05.

4. Discussion

Within this study, we analyzed the role of RUE and LAI development in SRC poplar and AFCs in determining AGDM production. We hypothesized the importance of RUE and LAI for AGDM production in SRC poplar and AFCs, and also improved the estimation of AGDM production by using $\sum$LAI or $\sum$(LAI $\times$ IPAR) integrating the LAI development over the whole vegetation period.

The results of LAI development in SRC poplar show that the maximum occurs near the end of summer, which closely matches earlier studies for fast growing woody crops [27,47,60,61]. In these earlier studies, the LAI_{max} ranged from 3.5–10 m^2 m^{-2}, which may be attributed to the growing season's weather conditions and development of poplar canopy [27,62]. In our study, an increase of the LAI_{max} from 3.6–9.5 m^2 m^{-2} is evident after transition to coppice management. Likewise, Broeckx et al. [28] reported LAI_{max} values from 0.49–1.68 m^2 m^{-2} for one-year-old (first growing season) and 0.87–4.63 m^2 m^{-2} for two-year-old diverse poplar clones, while in other fast growing trees like eucalyptus and willow the LAI_{max} estimated values varied from 0.8–6.1 m^2 m^{-2} and from 2.4–6.7 m^2 m^{-2}, respectively. In poplar, the LAI development dynamics is also delayed after coppice. The LAI increment rate increases particularly in the first three years after coppice and reaches similar LAI development dynamics as uncoppiced canopy. The data confirm the positive effect of coppice management on the LAI development and canopy closure [28,47,63].

In our study, the LAI_{max} values for AFCs are in close agreement with the LAI_{max} reported in WW, SB, SM, and OR [24,64–67]. Variations in the LAI_{max} values are related to genotype, site (particularly soil conditions), length of the growing season, sowing density, and the availability of water and nutrients [27,68]. The LAI_{max} may be strongly limited by reduced water availability resulting in reduced growth, yield, and yield components [69,70].

Besides LAI development in SRC poplar and AFCs, our LAD results were similar to previous studies where the LAD range varied between 58 and 180 days in AFCs (C_3 and C_4 crops) and SRC [28,47,68,71]. Higher LAI and LAD were achieved in SRC poplar as compared to AFCs because woody crops are taller, multi stemmed, and their developed roots systems may accommodate higher canopy closure as compared to AFCs [25,26,54]. The responses of LAI develoment in SRC poplar and AFCs can be potentially used for the screening of genotypes under stress conditions or for the development of adaptation management strategies to reduce climate change impacts. Some earlier studies have mentioned the importance of LAI measurements in different ecosystems for process-based models such as APEX and ALMANAC, which were used for the prediction of climate change impacts on SRC poplar and crop productivity [72–74]. Thus, our findings may contribute to improving the models as well as to help farmers in better selection of crops for future climates together with fulfilling the growing requirements for food and green-energy production [35].

Plant species show relatively high differences in RUE [16,30], however, the long term average of RUE for fast growing poplar was comparable to data published by Linderson et al. [52] who estimated RUE at 1.40 g MJ^{-1} for willow clones in Scania and also to some studies for poplar plantations where the RUE varied between 1 and 2 g MJ^{-1} [31,36,40]. In contrast, Broeckx et al. [28] reported lower RUE values varying between 0.29 and 0.68 and an average RUE of 0.50 g MJ^{-1} in twelve poplar clones in Flanders, Belgium. Low or high RUE values are characteristic of the biomass accumulation rate, are site specific (water and nutrient availability), depend on the length of growing season, as well as the height and age of trees and genotypes [36]. In our study, the RUE values varied between individual crops and growing seasons, however, the long-term average was higher in AFCs compared to SRC poplar. It may be due to differences in crop physiology [12,75] and nutrient effects [64,76] as the effect of nutrition (particularly N) increases RUE. RUE is increased by higher N doses [16,77] and can be stimulated also by a higher availability of P and K [78–80]. Higher RUE is often reported also for C_4 crops, but the differences in crop physiology depend greatly on environmental conditions, particularly temperature [25,81].

Our RUE values for SB and WW are similar to previous studies reviewed by Kemanian et al. [24]. We observed fairly low RUE for OR (0.79 g MJ^{-1}) and SM (1.19 g MJ^{-1}) as compared to previous studies, where Kuai et al. [67] and Williams et al. [82] reported 1.07–1.09 g MJ^{-1} in OR and 1.71 g MJ^{-1} in maize, respectively. RUE values may be increased by favorable conditions such as higher water and nutrient (particularly N) availability [13,52,68,83]. RUE could also be affected by sowing density and genotype. Higher RUE was found in higher densities [27,52,67].

The growth and biomass production of poplar was in accordance with our earlier data [41]. Compared to other studies, depending on climate and management (plant spacing, irrigation, fertilization, and genotypes), a production of 10–15 t ha^{-1} $year^{-1}$ could be expected [84,85]. Thus, the average productivity observed in our study, despite relatively low precipitation, and soil water recharge, is acceptable. However, in some cases the average AGDM production observed is substantially higher, mainly due to favorable climatic condition, the length of rotation cycle, genotype, higher nutrients, and water availability [86–89]. In our study, AGDM production uniformly increased season by season in SRC poplar (PU and PC) which can be attributed to the development of the root system and the increasing capacity to capture water and nutrients.

In earlier studies, AGDMs of 5.6 t ha^{-1} for barley in Pakistan [64] and 10.3–14.2 t ha^{-1} in the USA [22] were observed, for wheat 5.3–6.7 t ha^{-1} in China [79] and 5.74–7.22 t ha^{-1} in Pakistan [64], for maize 14.5–14.9 t ha^{-1} in different water regimes for many years in China [80], and for oilseed rape 3.6–4.7 t ha^{-1} for many cultivars in the Czech Republic and other European countries [90] which is in accordance with our data.

However, in some studies, the AGDM varied only between 1.82 and 2.9 t ha^{-1} for AFCs [91,92]. Such a low productivity could be related to unfavorable climatic conditions with poor availability of water and nutrients in particular places. Lower AGDM production in OR-R and SM-M within our study could be attributed to lower soil fertility and lower temperatures in a given region, resulting also in a shorter vegetation period. OR requires high nutrient availability, while SM is mainly affected by temperature. Higher temperature requirements are typical for C_4 crops [93,94].

The moderate positive relationships between LAI_{max} and AGDM production in poplar clone J-105 are in accordance with our previous studies [47]. In AFCs, the AGDM production varied between years, as a result of season (weather conditions), fertilizers applied to individual crops, and crop physiology. Our results confirm the earlier observations for a strong and positive correlation between RUE and AGDM production in high density poplar genotypes and AFCs [22,26,29,35].

The relationships between LAI or RUE and AGDM production show shifts between SRC poplar and AFCs indicating changes in the relative contribution to biomass. These results suggest that the biomass production improvement by selecting poplar and AFCs cultivars for specific growth parameters should take crop management, and consequently RUE into account. Our data also demonstrated the role of RUE for AGDM production in C_3 and C_4 crops.

5. Conclusions

Our study shows LAI to be high in SRC poplar compared to AFCs while RUE was shown to be higher in AFCs than SRC poplar. Both high LAI and RUE could be responsible for high biomass accumulation in SRC poplar; while in AFCs, the biomass accumulation is related mainly to RUE. The AGDM estimation by LAI in SRC poplar was improved by using the sum of LAI over the whole vegetation period and the sum of LAI multiplied by IPAR. The RUE can be thus considered as an important determinant of biomass production in both SRC poplar and AFCs while LAI could be a good biomass predictor in only SRC poplar. The evaluation of plant productivity for food and energy security under climate change is unlikely to be achieved without improving the model with LAI and RUE input and the right decisions for crop rotations in the changing environment. This is conditioned by a better understanding of the LAI development, the phenology of the plants, and the role of RUE and LAI in regulating productivity and plant adaption to climate change in different crops such as fast-growing trees and AFCs.

Overall, we can conclude that this long-term study is useful particularly for poplar biomass estimation under different environmental conditions or seasonal changes. The data can serve to improve the modeling of LAI, RUE, and AGDM development for precise forecasting in the climate change era.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/4/168/s1, Figure s1: Development of an allometric relationship between aboveground dry mass (AGDM, kg stump^{-1}) and in diameter at breast height (DBH, mm) of poplar clone J-105 in coppice rotation after two years of plant growth.

Acknowledgments: The study was supported by the Ministry of Education, Youth and Sports (project CzeCOS No. LM2015061 and CzeCOS ProCES No. CZ.02.1.01/0.0/0.0/16_013/0001609). We are also thankful to the internal grant agency (IGA 53/2014) at the Mendel University in Brno, Czech Republic.

Author Contributions: A.M.T., M.F., M.T. and M.V.M. conceived and designed the study. A.M.T., E.P., M.O. and M.F. performed the experiment and also participated in the data collection and cleaning. A.M.T. and K.K. analyzed the data and wrote the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

∑LAI	Sum of leaf area index
AFCs	Annual field crops
AGDM	Aboveground dry mass
DBH	Diameter at breast height (mm)
DM	Dry mass

IPAR	Intercepted photosynthetically active radiation (MJ m^{-2})
LAD	Leaf area duration (days)
LAI	Leaf area index (m^2 m^{-2})
LAI_{max}	Maximum leaf area index
LAI_{mean}	Mean leaf area index
OR	Oilseed rape
OR-R	Oilseed rape cultivar Rohan
PAR	Photosynthetically active radiation
PC	Poplar coppiced
PU	Poplar uncoppiced
RUE	Radiation use efficiency (g MJ^{-1})
SB	Spring barley
SB-B	Spring barley cultivar Bojos
SB-T	Spring barley cultivar Tolar
SM	Silage maize
SM-M	Silage maize cultivar MON3301
SRC	Short rotation coppice
WW	Winter wheat
WW-E	Winter wheat cultivar Etela

References

1. IPCC (Intergovernmental Panel on Climate Change). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014; ISBN 9789291691432.
2. Pinstrup-Andersen, P. Food security: Definition and measurement. *Food Secur.* **2009**, *1*, 5–7. [CrossRef]
3. Popp, J.; Lakner, Z.; Harangi-Rákos, M.; Fári, M. The effect of bioenergy expansion: Food, energy, and environment. *Renew. Sustain. Energy Rev.* **2014**, *32*, 559–578. [CrossRef]
4. Scarlat, N.; Dallemand, J.F. Recent developments of biofuels/bioenergy sustainability certification: A global overview. *Energy Policy* **2011**, *39*, 1630–1646. [CrossRef]
5. Busetto, L.; Casteleyn, S.; Granell, C.; Pepe, M.; Barbieri, M.; Campos-Taberner, M.; Casa, R.; Collivignarelli, F.; Confalonieri, R.; Crema, A.; et al. Downstream services for rice crop monitoring in Europe: From regional to local scale. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2017**, *10*, 5423–5441. [CrossRef]
6. Dimitriou, I.; Baum, C.; Baum, S.; Busch, G.; Schulz, U.; Köhn, J.; Lamersdorf, N.; Leinweber, P.; Aronsson, P.; Weih, M.; et al. *Quantifying Environmental Effects of Short Rotation Coppice (SRC) on Biodiversity, Soil and Water*; IEA Bioenergy Task 43, Report 2011; IEA: Paris, France, 2011; p. 34.
7. Kauter, D.; Lewandowski, I.; Claupein, W. Quantity and quality of harvestable biomass from Populus short rotation coppice for solid fuel use—A review of the physiological basis and management influences. *Biomass Bioenergy* **2003**, *24*, 411–427. [CrossRef]
8. Timmer, C.P. The macro dimensions of food security: Economic growth, equitable distribution, and food price stability. *Food Policy* **2000**, *25*, 283–295. [CrossRef]
9. Wheeler, T.; von Braun, J. Climate change impacts on global food security. *Science* **2013**, *341*, 508–513. [CrossRef] [PubMed]
10. Ewert, F. Modelling plant responses to elevated CO_2: How important is leaf area index? *Ann. Bot.* **2004**, *93*, 619–627. [CrossRef] [PubMed]
11. Chen, J.M.; Black, T.A. Defining leaf area index for non-flat leaves. *Plant Cell Environ.* **1992**, *15*, 421–429. [CrossRef]
12. Monteith, J.L. Reassessment of maximum growth rates for C3 and C4 Crops. *Exp. Agric.* **1978**, *14*, 1–5. [CrossRef]
13. Biscoe, P.V.; Gallagher, J.N. Weather, dry matter production and yield. In *Environmental Effects on Crop Physiology; Proceedings of the a Symposium Held at Long Ashton Research Station, University of Bristol, Bristol, UK, 13–16 April 1975*; Academic Press: New York, NY, USA, 1977.

14. Hangs, R.D.; Van Rees, K.C.J.; Schoenau, J.J.; Guo, X. A simple technique for estimating above-ground biomass in short-rotation willow plantations. *Biomass Bioenergy* **2011**, *35*, 2156–2162. [CrossRef]
15. Hikosaka, K. Leaf canopy as a dynamic system: Ecophysiology and optimality in leaf turnover. *Ann. Bot.* **2005**, *95*, 521–533. [CrossRef] [PubMed]
16. Sinclair, T.R.; Horie, T. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. *Crop Sci.* **1989**, *29*, 90. [CrossRef]
17. Sinclair, T.R.; Shiraiwa, T.; Hammer, G.L. Variation in crop radiation-use efficiency with increased diffuse radiation. *Crop Sci.* **1992**, *32*, 1281–1284. [CrossRef]
18. Medlyn, B.E. Physiological basis of the light use efficiency model. *Tree Physiol.* **1998**, *18*, 167–176. [CrossRef] [PubMed]
19. Liu, W.; Yan, J.; Li, J.; Sang, T. Yield potential of *Miscanthus* energy crops in the Loess Plateau of China. *GCB Bioenergy* **2012**, *4*, 545–554. [CrossRef]
20. Stockle, C.O.; Kiniry, J.R. Variability in crop radiation-use efficiency associated with vapor-pressure deficit. *Field Crop. Res.* **1990**, *25*, 171–181. [CrossRef]
21. Larson, P.R.; Isebrands, J.G. The relation between leaf production and wood weight in first-year root sprouts of two *Populus* clones. *Can. J. For. Res.* **1972**, *2*, 98–104. [CrossRef]
22. Bartelink, H.H. A growth model for mixed forest stands. *For. Ecol. Manag.* **2000**, *134*, 29–43. [CrossRef]
23. Bartelink, H.H.; Kramer, K.; Mohren, G.M.J. Applicability of the radiation-use efficiency concept for simulating growth of forest stands. *Agric. For. Meteorol.* **1997**, *88*, 169–179. [CrossRef]
24. Kemanian, A.R.; Stöckle, C.O.; Huggins, D.R. Variability of barley radiation-use efficiency. *Crop Sci.* **2004**, *44*, 1662–1672. [CrossRef]
25. Jamieson, P.D.; Martin, R.J.; Francis, G.S.; Wilson, D.R. Drought effects on biomass production and radiation-use efficiency in barley. *Field Crop. Res.* **1995**, *43*, 77–86. [CrossRef]
26. Zahoor, A.; Riaz, M.; Ahmad, S.; Ali, H.; Khan, M.B.; Javed, K.; Anjum, M.A.; Zia-Ul-Haq, M.; Khan, M.A. Ontogeny growth and radiation use efficiency of *Helianthus annuus* L., as affected by hybrids, nitrogenous regimes and planting geometry under irrigated arid conditions. *Pak. J. Bot.* **2010**, *42*, 3197–3207.
27. Ceulemans, R.; McDonald, A.J.S.; Pereira, J.S. A comparison among eucalypt, poplar and willow characteristics with particular reference to a coppice, growth-modelling approach. *Biomass Bioenergy* **1996**, *11*, 215–231. [CrossRef]
28. Broeckx, L.; Vanbeveren, S.; Verlinden, M.; Ceulemans, R. First vs. second rotation of a poplar short rotation coppice: Leaf area development, light interception and radiation use efficiency. *iForest-Biogeosci. For.* **2015**, e1–e9. [CrossRef]
29. Kiniry, J.R. Biomass accumulation and radiation use efficiency of honey mesquite and eastern red cedar. *Biomass Bioenergy* **1998**, *15*, 467–473. [CrossRef]
30. Kiniry, J.R.; Jones, C.A.; O'toole, J.C.; Blanchet, R.; Cabelguenne, M.; Spanel, D.A. Radiation-use efficiency in biomass accumulation prior to grain-filling for five grain-crop species. *Field Crop. Res.* **1989**, *20*, 51–64. [CrossRef]
31. Landsberg, J.J.; Wright, L.L. Comparisons among *Populus* clones and intensive culture conditions, using an energy-conservation model. *For. Ecol. Manag.* **1989**, *27*, 129–147. [CrossRef]
32. Iio, A.; Hikosaka, K.; Anten, N.P.R.; Nakagawa, Y.; Ito, A. Global dependence of field-observed leaf area index in woody species on climate: A systematic review. *Glob. Ecol. Biogeogr.* **2014**, *23*, 274–285. [CrossRef]
33. Wright, I.J.; Groom, P.K.; Lamont, B.B.; Poot, P.; Prior, L.D.; Reich, P.B.; Schulze, E.D.; Veneklaas, E.J.; Westoby, M. Leaf trait relationships in Australian plant species. *Funct. Plant Biol.* **2004**, *31*, 551–558. [CrossRef]
34. Asner, G.P.; Scurlock, J.M.O.; Hicke, J.A. Global synthesis of leaf area index observations. *Glob. Ecol. Biogeogr.* **2003**, *12*, 191–205. [CrossRef]
35. Harrington, R.A.; Fownes, J.H.; Meinzer, F.C.; Scowcroft, P.G. Forest growth along a rainfall gradient in Hawaii: *Acacia koa* stand structure, productivity, foliar nutrients, and water- and nutrient-use efficiencies. *Oecologia* **1995**, *102*, 277–284. [CrossRef] [PubMed]
36. Cannell, M.G.R.; Sheppard, L.J.; Milne, R. Light use efficiency and woody biomass production of Poplar and Willow. *Forestry* **1988**, *61*, 125–136. [CrossRef]
37. Haxeltine, A.; Prentice, I.C. BIOME 3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability and competition among plant functional types. *Glob. Biogeochem. Cycles* **1996**, *10*, 693–709. [CrossRef]

38. Choudhury, B.J. Modeling radiation- and carbon-use efficiencies of maize, sorghum, and rice. *Agric. For. Meteorol.* **2001**, *106*, 317–330. [CrossRef]
39. Wolf, J.; Evans, L.G.; Semenov, M.A.; Eckersten, H.; Iglesias, A. Comparison of wheat simulation models under climate change. I. Model calibration and sensitivity analyses. *Clim. Res.* **1996**, *7*, 253–270. [CrossRef]
40. Green, D.S.; Kruger, E.L.; Stanosz, G.R.; Isebrands, J.G. Light-use efficiency of native and hybrid poplar genotypes at high levels of intracanopy competition. *Can. J. For. Res.* **2001**, *31*, 1030–1037. [CrossRef]
41. Trnka, M.; Trnka, M.; Fialová, J.; Koutecký, V.; Fajman, M.; Žalud, Z.; Hejduk, S. Biomass production and survival rates of selected poplar clones grown under a short-rotation system on arable land. *Plant Soil Environ.* **2008**, *54*, 78–88. [CrossRef]
42. Fischer, M.; Orság, M.; Trnka, M.; Pohanková, E.; Hlavinka, P.; Tripathi, A.M.; Žalud, Z. Annual and intra-annual water balance components of a short rotation poplar coppice based on sap flow and micrometeorological and hydrological approaches. *Acta Hortic.* **2013**. [CrossRef]
43. Pohanková, E.; Hlavinka, P.; Takáč, J.; Žalud, Z.; Trnka, M. Calibration and validation of the crop growth model daisy for spring barley in the Czech Republic. *Acta Univ. Agric. Silvic. Mendel. Brun.* **2015**, *63*. [CrossRef]
44. Bonhomme, R. Beware of comparing RUE values calculated from PAR vs solar radiation or absorbed vs intercepted radiation. *Field Crop. Res.* **2000**, *68*, 247–252. [CrossRef]
45. Bréda, N.J.J. Ground-based measurements of leaf area index: A review of methods, instruments and current controversies. *J. Exp. Bot.* **2003**, *54*, 2403–2417. [CrossRef] [PubMed]
46. Campos-Taberner, M.; García-Haro, F.J.; Confalonieri, R.; Martínez, B.; Moreno, Á.; Sánchez-Ruiz, S.; Gilabert, M.A.; Camacho, F.; Boschetti, M.; Busetto, L. Multitemporal monitoring of plant area index in the Valencia rice district with PocketLAI. *Remote Sens.* **2016**, *8*. [CrossRef]
47. Tripathi, A.M.; Fischer, M.; Orság, M.; Marek, M.V.; Žalud, Z.; Trnka, M. Evaluation of indirect measurement method of seasonal patterns of leaf area index in a high-density short rotation coppice culture of poplar. *Acta Univ. Agric. Silvic. Mendel. Brun.* **2016**, *64*, 549–556. [CrossRef]
48. Liu, G.; Xie, Y.; Gao, X.F.; Duan, X.W. Application of SunScan canopy analysis system in measuring leaf area index of soybean. *Chin. J. Ecol.* **2008**, *27*, 862–866.
49. Oguntunde, P.G.; Olukunle, O.J.; Fasinmirin, J.T.; Abiolu, O.A. Performance of the SunScan canopy analysis system in estimating leaf area index of maize. *Agric. Eng. Int. CIGR J.* **2012**, *14*, 1–7.
50. Wilhelm, W.W.; Ruwe, K.; Schlemmer, M.R. Comparison of three leaf area index meters in a corn canopy. *Crop Sci.* **2000**, *40*, 1179–1183. [CrossRef]
51. Schirrmann, M.; Hamdorf, A.; Giebel, A.; Dammer, K.H.; Garz, A. A mobile sensor for leaf area index estimation from canopy light transmittance in wheat crops. *Biosyst. Eng.* **2015**, *140*, 23–33. [CrossRef]
52. Linderson, M.L.; Iritz, Z.; Lindroth, A. The effect of water availability on stand-level productivity, transpiration, water use efficiency and radiation use efficiency of field-grown willow clones. *Biomass Bioenergy* **2007**, *31*, 460–468. [CrossRef]
53. Fischer, M.; Trnka, M.; Kučera, J.; Fajman, M.; Žalud, Z. Biomass productivity and water use relation in short rotation poplar coppice (*Populus nigra* × *P. maximowiczii*) in the conditions of Czech Moravian Highlands. *Acta Univ. Agric. Silvic. Mendel. Brun.* **2011**, *59*, 141–152. [CrossRef]
54. Ketterings, Q.M.; Coe, R.; Van Noordwijk, M.; Ambagau, Y.; Palm, C.A. Reducing uncertainty in the use of allometric biomass equations for predicting above-ground tree biomass in mixed secondary forests. *For. Ecol. Manag.* **2001**, *146*, 199–209. [CrossRef]
55. Basuki, T.M.; van Laake, P.E.; Skidmore, A.K.; Hussin, Y.A. Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *For. Ecol. Manag.* **2009**, *257*, 1684–1694. [CrossRef]
56. Monsi, M.; Saeki, T. Uber den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung fur die Stoffproduktion. *Jpn. J. Bot.* **1953**, *14*, 22–52.
57. Kemanian, A.R.; Stöckle, C.O.; Huggins, D.R. Transpiration-use efficiency of barley. *Agric. For. Meteorol.* **2005**, *130*, 1–11. [CrossRef]
58. Heidari, H.; Johansooz, M.R.; Hosseini, S.M.B.; Chaichi, M.R. Alternate furrow irrigation effect on radiation use efficiency and forage quality of foxtail millet (*Setaria italica*). *Ann. Biol. Res.* **2012**, *3*, 2565–2574.
59. Ajit; Das, D.K.; Chaturvedi, O.P.; Jabeen, N.; Dhyani, S.K. Predictive models for dry weight estimation of above and below ground biomass components of *Populus deltoides* in India: Development and comparative diagnosis. *Biomass Bioenergy* **2011**, *35*, 1145–1152. [CrossRef]

60. Howe, G.T.; Saruul, P.; Davis, J.; Chen, T.H.H. Quantitative genetics of bud phenology, frost damage, and winter survival in an F2 family of hybrid poplars. *Theor. Appl. Genet.* **2000**, *101*, 632–642. [CrossRef]
61. Tharakan, P.J.; Volk, T.A.; Nowak, C.A.; Ofezu, G.J. Assessment of canopy structure, light interception, and light-use efficiency of first year regrowth of shrub willow (Salix sp.). *BioEnergy Res.* **2008**, *1*, 229–238. [CrossRef]
62. Ceulemans, R.; Stettler, R.F.; Hinckley, T.M.; Isebrands, J.G.; Heilman, P.E. Crown architecture of *Populus* clones as determined by branch orientation and branch characteristics. *Tree Physiol.* **1990**, *7*, 157–167. [CrossRef] [PubMed]
63. Rae, A.M.; Robinson, K.M.; Street, N.R.; Taylor, G. Morphological and physiological traits influencing biomass productivity in short-rotation coppice poplar. *Can. J. For. Res.* **2004**, *34*, 1488–1498. [CrossRef]
64. Ahmad, S.; Ali, H.; Ismail, M.; Shahzad, M.I.; Nadeem, M.; Anjum, M.A.; Zia-Ul-Haq, M.; Firdous, N.; Khan, M.A. Radiation and nitrogen use efficiencies of C3 winter cereals to nitrogen split application. *Pak. J. Bot.* **2012**, *44*, 139–149.
65. Choudhury, B.J. A sensitivity analysis of the radiation use efficiency for gross photosynthesis and net carbon accumulation by wheat. *Agric. For. Meteorol.* **2000**, *101*, 217–234. [CrossRef]
66. Timlin, D.J.; Fleisher, D.H.; Kemanian, A.R.; Reddy, V.R. Plant density and leaf area index effects on the distribution of light transmittance to the soil surface in maize. *Agron. J.* **2014**, *106*, 1828–1837. [CrossRef]
67. Kuai, J.; Sun, Y.; Zuo, Q.; Huang, H.; Liao, Q.; Wu, C.; Lu, J.; Wu, J.; Zhou, G. The yield of mechanically harvested rapeseed (*Brassica napus* L.) can be increased by optimum plant density and row spacing. *Sci. Rep.* **2015**, *5*. [CrossRef] [PubMed]
68. Watson, D.J. Comparative physiological studies on the growth of field crops. *Ann. Appl. Biol.* **1947**, *11*, 41–76. [CrossRef]
69. García Del Moral, L.F.; Rharrabti, Y.; Villegas, D.; Royo, C. Evaluation of grain yield and its components in durum wheat under Mediterranean conditions: An ontogenic approach. *Agron. J.* **2003**, *95*, 266–274. [CrossRef]
70. Guttieri, M.J.; Stark, J.C.; O'Brien, K.; Souza, E. Relative sensitivity of spring wheat grain yield and quality parameters to moisture deficit. *Crop Sci.* **2001**, *41*, 327–335. [CrossRef]
71. Richards, R.; Townley-Smith, T. Variation in leaf area development and its effect on water use, yield and harvest index of droughted wheat. *Aust. J. Agric. Res.* **1987**, *38*, 983–992. [CrossRef]
72. Johnson, E. Goodbye to carbon neutral: Getting biomass footprints right. *Environ. Impact Assess. Rev.* **2009**, *29*, 165–168. [CrossRef]
73. Guo, L.; Dai, J.; Wang, M.; Xu, J.; Luedeling, E. Responses of spring phenology in temperate zone trees to climate warming: A case study of apricot flowering in China. *Agric. For. Meteorol.* **2015**, *201*, 1–7. [CrossRef]
74. Jiang, R.; Wang, T.; Shao, J.; Guo, S.; Zhu, W.; Yu, Y.J.; Chen, S.L.; Hatano, R. Modeling the biomass of energy crops: Descriptions, strengths and prospective. *J. Integr. Agric.* **2017**, *16*, 1197–1210. [CrossRef]
75. Piedade, M.T.F.; Junk, W.J.; Long, S.P. The productivity of the C4 grass *Echinochloa polystachya* on the Amazon floodplain. *Ecology* **1991**, *72*, 1456–1463. [CrossRef]
76. Muurinen, S.; Peltonen-Sainio, P. Radiation-use efficiency of modern and old spring cereal cultivars and its response to nitrogen in northern growing conditions. *Field Crop. Res.* **2006**, *96*, 363–373. [CrossRef]
77. Cassman, K.G.; Dobermann, A.; Walters, D.T. Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio* **2002**, *31*, 132–140. [CrossRef] [PubMed]
78. Plenet, D.; Mollier, A.; Pellerin, S. Growth analysis of maize field crops under phosphorus deficiency. II. Radiation-use efficiency, biomass accumulation and yield components. *Plant Soil.* **2000**, *224*, 259–272. [CrossRef]
79. Li, Q.; Liu, M.; Zhang, J.; Dong, B.; Bai, Q. Biomass accumulation and radiation use efficiency of winter wheat under deficit irrigation regimes. *Plant Soil Environ.* **2009**, *2009*, 85–91. [CrossRef]
80. Li, Q.; Chen, Y.; Liu, M.; Zhou, X.; Yu, S.; Dong, B. Effects of irrigation and planting patterns on radiation use efficiency and yield of winter wheat in North China. *Agric. Water Manag.* **2008**, *95*, 469–476. [CrossRef]
81. Goyne, P.J.; Milroy, S.P.; Lilley, J.M.; Hare, J.M. Radiation interception, radiation use efficiency and growth of barley cultivars. *Aust. J. Agric. Res.* **1993**, *44*. [CrossRef]
82. Williams, W.; Loomis, R.; Lepley, C. Vegetative growth of corn as affected by population density. I. Productivity in relation to interception of solar radiation. *Crop Sci.* **1965**, *5*, 211–215. [CrossRef]

83. Kiniry, J.R.; Landivar, J.A.; Witt, M.; Gerik, T.J.; Cavero, J.; Wade, L.J. Radiation-use efficiency response to vapor pressure deficit for maize and sorghum. *Field Crop. Res.* **1998**, *56*, 265–270. [CrossRef]
84. Deckmyn, G.; Laureysens, I.; Garcia, J.; Muys, B.; Ceulemans, R. Poplar growth and yield in short rotation coppice: Model simulations using the process model SECRETS. *Biomass Bionergy* **2004**, *26*, 221–227. [CrossRef]
85. Verlinden, M.S.; Broeckx, L.S.; Van den Bulcke, J.; Van Acker, J.; Ceulemans, R. Comparative study of biomass determinants of 12 poplar (*Populus*) genotypes in a high-density short-rotation culture. *For. Ecol. Manag.* **2013**, *307*, 101–111. [CrossRef]
86. Bungart, R.; Hüttl, R.F. Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget. *Eur. J. For. Res.* **2004**, *123*, 105–115. [CrossRef]
87. Scaracia-Mugnozza, G.E.; Ceulemans, R.; Heilman, P.E.; Isebrands, J.G.; Stettler, R.F.; Hinckley, T.M. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. *Can. J. For. Res.* **1997**, *27*, 285–294. [CrossRef]
88. Dunlap, J.M.; Stettler, R.F. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. X. Trait correlations in young black cottonwood from four river valleys in Washington. *Trees Struct. Funct.* **1998**, *13*, 28–39. [CrossRef]
89. Heilman, P.E.; Stettler, R.F. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. IV. Performance in short-rotation coppice. *Can. J. For. Res.* **1990**, *20*, 1257–1264. [CrossRef]
90. Nedomova, L. *Adriana, Müller 24—Rape Varieties with Excellent Yield from the BOR, Ltd. A Sbornik z Konference Prosperujici Olejniny*; CZU: Prague, Czech Republic, 2012; pp. 120–122.
91. Diepenbrock, W. Yield analysis of winter oilseed rape (*Brassica napus* L.): A review. *Field Crop. Res.* **2000**, *67*, 35–49. [CrossRef]
92. Spiertz, J.H.J.; Ellen, J. Effects of nitrogen on crop development and grain growth of winter in relation to assimilate and utilization of assimilates and nutrients. *Neth. J. Agric. Sci.* **1978**, *26*, 210–231.
93. Massad, R.S.; Tuzet, A.; Bethenod, O. The effect of temperature on C4-type leaf photosynthesis parameters. *Plant Cell Environ.* **2007**, *30*, 1191–1204. [CrossRef] [PubMed]
94. Sage, R.F.; Kubien, D.S. The temperature response of C3 and C4 photosynthesis. *Plant Cell Environ.* **2007**, *30*, 1086–1106. [CrossRef] [PubMed]