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RESEARCH ARTICLE

Radiation use efficiency of maize under high-density optimal growth conditions in Jilin Province, China

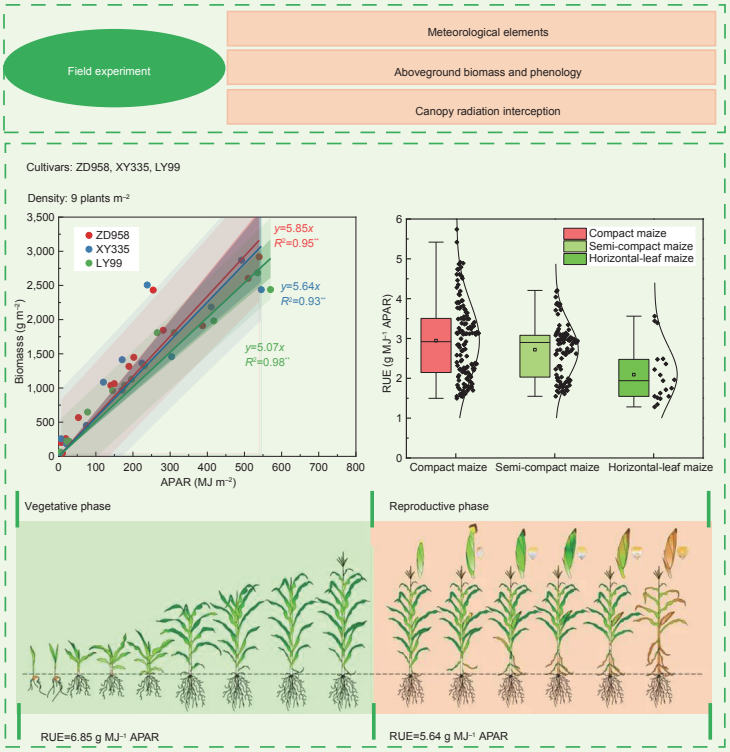
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Highlights

- During the entire growth period, maize radiation use efficiency (RUE) averaged 5.71 g MJ^{-1} absorbed photosynthetically active radiation (APAR) under high-density optimal growth conditions.
- Within the vegetative and reproductive growth periods, maize RUE averaged 6.85 and 5.64 g MJ^{-1} APAR, respectively.
- An RUE of 5.07–5.85 g MJ^{-1} APAR can be used to derive the optimal potential yield in maize simulation models.

Graphical abstract



APAR, absorbed photosynthetically active radiation; RUE, absorbed photosynthetically active radiation. **, $P<0.01$.

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Abstract

To evaluate the impact of climate change on maize production, accurately measuring the radiation use efficiency (RUE) of maize is critical. This study focused on three maize cultivars in Jilin Province, China: Zhengdan 958 (ZD958), Xianyu 335 (XY335), and Liangyu 99 (LY99). Under the optimal growing conditions for high density planting (9 plants m^{-2}), the maize RUE was determined during the vegetative and reproductive phases, and the entire growth period. The results showed that the canopy light interception for maize peaked during anthesis. After anthesis, maize plant biomass continued to accumulate. The maize RUE was calculated based on the absorbed photosynthetically active radiation (APAR). During the entire growth period, maize RUE averaged 5.71 g MJ^{-1} APAR among the three cultivars, with a high-to-low order of ZD958 (5.85 g MJ^{-1} APAR)>XY335 (5.64 g MJ^{-1} APAR)>LY99 (5.07 g MJ^{-1} APAR). Within the vegetative and reproductive growth periods, maize RUE averaged 6.85 and 5.64 g MJ^{-1} APAR, respectively. When utilizing maize models that depend on RUE to predict aboveground biomass accumulation, such as APSIM, the current RUE value of 3.6 g MJ^{-1} APAR is considerably lower than the measured value obtained under high-density optimal growing conditions. Consequently, to derive the optimal potential yield for maize in such planting conditions, we recommend adjusting the RUE to a range of 5.07–5.85 g MJ^{-1} APAR.

Keywords: radiation use efficiency (RUE), absorbed photosynthetically active radiation (APAR), maize cultivars, growth period, high density

1. Introduction

Maize is the main staple and fodder crop around the world. In China, the total maize production was 260.9 million tons in 2020, which accounted for 22.4% of the global total maize production, second only to the United States (360.3 million tons) (FAO 2021). Maize production is determined by the yield per unit area and the total planting area. Increasing the planting area for maize in China has been a major challenge. Hence, increasing maize production lies in improving the yield per unit area (Wu *et al.* 2021). In recent years, the joint efforts of utilizing new maize varieties and adopting effective agronomic practices have led to a steady increase in maize yields in China (Liu *et al.* 2021b). However, a substantial gap remains between the achieved and attainable yields (Sun *et al.* 2021).

Photosynthesis, the fundamental process for crop yield development, enables the conversion of light energy into chemical energy in crops and natural vegetation (Smith *et al.* 2023). In the case of maize, photosynthesis plays a pivotal role as more than 80% of its dry matter is derived from photosynthesis (Pernollet *et al.* 1986; Echarte *et al.* 2008). Solar radiation plays a vital role in providing the energy required for photosynthesis. Theoretical studies and experimental observations have consistently shown that plant photosynthesis is positively influenced by the intensity of irradiance (Williams *et al.* 2016). From 1985 to 2014, the increase in solar radiation during grain filling contributed approximately 28.8% of the increase in maize production in China (Liu *et al.* 2021b). Biomass accumulation can be simplified as the product of intercepted radiation and radiation use efficiency (RUE) without considering other environmental factors (Stöckle and Kemanian 2009). Without significant changes in solar radiation, increasing plant RUE can effectively enhance dry matter accumulation and ultimately increase the crop yield. Crop RUE is a critical adaptive feature for quantifying the potential amount of aboveground biomass generated by crops per unit of solar interception (Wu *et al.* 2024).

Compared to other cultivation practices, changing the plant density can significantly affect the canopy structure and light energy utilization of maize (Li and Li 2004). The canopy structure also directly affects the distribution of light and RUE within the maize canopy (Liu G *et al.* 2017; Shi *et al.* 2022). By optimizing the canopy structure of maize, the RUE and the photosynthetic rate of maize leaves can be improved, hence increasing maize yield (Xue *et al.* 2016; Liu *et al.* 2019; Liu X *et al.* 2023). The accumulation of dry matter in plants depends on two key factors: the amount of incident photosynthetically active radiation (IPAR) absorbed by the canopy and the efficiency of converting that absorbed PAR into dry matter (i.e., RUE). The main physiological differences of C_3 plants can be reflected in the maximum RUE. RUE varies among different crop types and even between different growth stages for a given crop (Shi *et al.* 2022). Generally, the maximum RUE for maize occurs during the vegetative phase (Muchow and Davis 1988; Shi *et al.* 2022).

To estimate crop production on a regional scale, it is crucial to accurately assess crop potential yield. Crop models are effective tools for estimating potential yield. The CERES, APSIM, and EPIC models already use the concept of RUE to estimate crop yields in different environments. In these crop models, the cumulative daily biomass is calculated as the product of radiation interception and RUE (MacKinnon 1987; Jones *et al.* 1991; Keating *et al.* 2003). Adopting new maize cultivars and increasing plant density can affect the RUE of maize canopies. However, the empirical values currently used in the models above may not adequately capture the impacts of these changes, resulting in greater uncertainty in the modeling predictions. Therefore, it is imperative to optimize the model parameters to improve crop simulation accuracy (Shi *et al.* 2022).

Northeast China is one of the primary maize-growing regions in China. Over the past 30 years, solar radiation during the growing season for maize has shown an increasing trend in this region (Liu *et al.* 2021a). Due to the

adoption of modern maize cultivars and the implementation of the maize high-yield cultivation technique featuring dense planting and precision irrigation and fertilization management, plant density has been increasing in Northeast China, which has significantly enhanced the yield in this region (Zhang *et al.* 2022; Shen *et al.* 2024). To estimate the maize yield potential for present conditions, the RUE parameter values used for modern maize cultivars grown at high density must be updated in the crop models (Sun *et al.* 2024). This study focused on three representative maize cultivars in Jilin Province of China. Based on a field experiment, RUE values were determined for modern maize cultivars grown under high planting density during the vegetative and reproductive phases, and the entire growing season.

2. Materials and methods

2.1. Study site

The field experiment was conducted at the Lishu Experimental Station of China Agricultural University (43°16′47′′N and 124°26′9′′E) in Jilin Province of China. The local climate is categorized as seasonal temperate semi-humid monsoon, and the soil is characterized as typic Hapludoll (or "Black Soil") (Soil Survey Staff 1998). From 1981 to 2018, the regional average temperature during the maize growing season was 20.3°C, total precipitation was 494 mm, and total solar radiation was 2,626.3 MJ m^{-2}.

2.2. Experimental design

The field experiment was conducted in 2021 and 2023. Three local maize cultivars were selected: Zhengdan 958 (ZD958), Xianyu 335 (XY335), and Liangyu 99 (LY99). ZD958 and XY335 are common and widely planted varieties in the maize planting areas of China that have different plant types, while LY99 is a high-yielding variety in Jilin. ZD958 is a compact variety, while XY335 and LY99 are semi-compact varieties. Compact maize is characterized by leaf up, an ear upper stem leaf angle of less than 25°, and an ear lower angle of less than 40°. Semi-compact maize is characterized by an angle between stems and leaves on the panicle of 25°–40°, and an angle between stems and leaves on the lower part of the panicle of 40°–55°. Each cultivar was planted at a high density of 9 plants m^{-2}, with three replications. Each plot was 10 m×15 m, the plants were placed 30–40 cm apart in each row, and the row spacing was 30 cm. Before sowing, the contents of N, P, K, pH and organic matter were measured in the 0–100 cm soil layers. The results were: organic matter, 21.0 g kg^{-1}; total nitrogen, 1.1 g kg^{-1}; pH 5.84; available phosphorus, 27.0 mg kg^{-1}; and rapidly available potassium, 146.7 mg kg^{-1}. For fertilization, 200 kg N ha^{-1}, 85 kg P ha^{-1}, and 90 kg K ha^{-1} were applied (as compound fertilizer-NPK). According to the local practice standards, single-cropping maize from May to September was adopted in the experiment. The sowing dates were May 16, 2021 and May 19, 2023. Intensive management was adopted to ensure optimal growth conditions, including adequate water and fertilizer, and total control of weeds and insects. The soil moisture content in the 0–100 cm soil layer was measured with a TRIME-TDR soil moisture content meter (IMKO, Germany) before sowing and during the maize growth stages. Irrigation was applied whenever the soil moisture content in the 0–100 cm soil layer was lower than 80% of the field capacity, and the irrigation method was flood irrigation. Herbicides were sprayed before sowing, and weeds were manually controlled during the maize growing season.

2.3. Data collection and analyses

Temperature, precipitation, and solar radiation were observed and recorded at a portable weather station near the experimental site. Data from May to September in both 2021 and 2023 are illustrated in Fig. 1.

The target stages included the 3-leaf, jointing, anthesis, silking, grain filling, and physiological maturity stages. Five sample plants were obtained from each plot for each target stage and dried for biomass measurement. The sample plants were heated at 105°C for 30 min and oven dried at (85±5)°C for about 3 days (Liu Z *et al.* 2023).

LI-190R point quantum sensors were installed in the plot to measure the incident and reflected quantum fluxes (μmol m^{-2} s^{-1}) above the canopy during the maize growing season. The intercepted quantum flux was measured with a single-line quantum sensor (LI-191R, LI-COR, USA) diagonally across the plant rows at the soil surface. All sensors were leveled

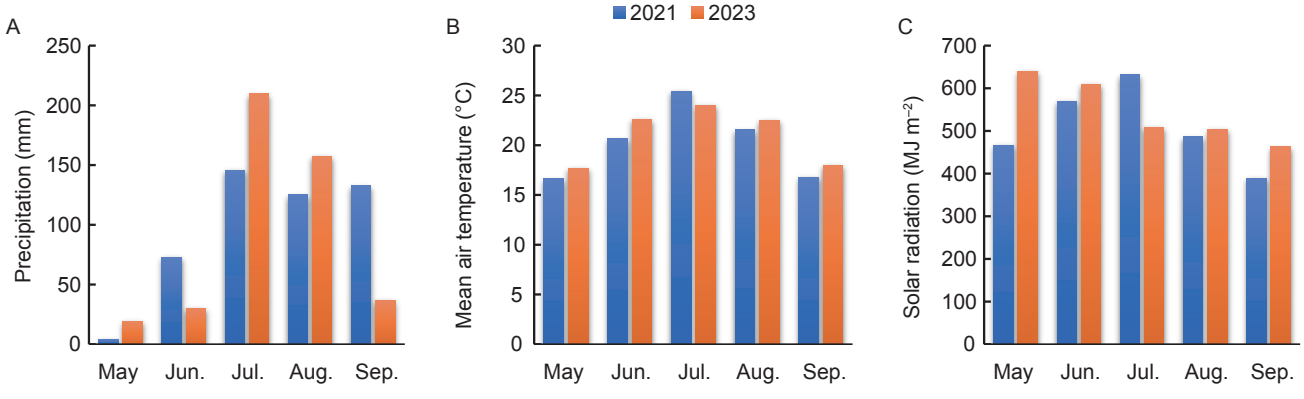


Fig. 1 Histograms of climatic conditions from May to September in 2021 and 2023 at the study site in Jilin Province, China. A, precipitation. B, mean air temperature. C, solar radiation.

and supported. The point-quantum sensor was installed 0.5 m above the canopy and adjusted during each target stage. The line quantum sensor was installed approximately 10 cm above the soil surface and routinely cleaned (every 3 and 5 days) to ensure reliable measurements. The schematic diagram of field measurements is illustrated in Fig. 2. All measurements of quantum flux (μmol m^{-2} s^{-1}) were then converted to PAR by using the conversion coefficient of 216.7 KJ mol^{-1} (Tollenaar and Bruulsema 1988; Tollenaar and Aguilera 1992). RUE is the micromoles of dry matter produced per mole of photosynthetically active photons absorbed by green canopy components (Kimball *et al.* 2002, Ceotto *et al.* 2013). RUE can be estimated by using the linear relationship between biomass accumulation and cumulative absorbed or intercepted PAR according to eqs. (1) and (2) (Sinclair and Muchow 1999):

$$RUE=\frac{W}{\sum APAR} \quad (1)$$

$$APAR=IPAR–TPAR–RPAR \quad (2)$$

where W is the observed aboveground biomass (g m^{-2}); APAR is the absorbed PAR (MJ m^{-2}); IPAR is the incident PAR (MJ m^{-2}); TPAR is the amount of PAR directly transmitted to the bottom of the canopy (MJ m^{-2}); and RPAR is the amount of PAR reflected from the canopy onto the ground surface (MJ m^{-2}) (Shi *et al.* 2022).

3. Results

3.1. Biomass accumulation during the growing season

Biomass accumulation before anthesis (development stage (DVS)<1.0) was similar for the three cultivars (Fig. 3). At anthesis (DVS=1.0), the aboveground biomass amounts were 1,243, 1,224, and 1,142 g m^{-2} for ZD958, XY335, and LY99, respectively. From anthesis to physiological maturity (1.0<DVS<2.0), the biomass accumulation for ZD958 was higher than those for XY335 and LY99. At physiological maturity (DVS=2.0), the aboveground biomass accumulation levels for ZD958, XY335, and LY99 were 2,760, 2,653, and 2,560 g m^{-2}, respectively. This indicates that ZD958 benefited more from the higher planting density compared to the other two maize cultivars.

3.2. Differences in IPAR before and after anthesis

In both study years, IPAR showed an increase over time before anthesis but barely changed after anthesis. In 2021, the fraction of IPAR was similar for the three cultivars, with values of 96.5, 97.4, and 97.7% for ZD958, XY335, and LY99, respectively. By comparison, the fraction of IPAR varied among the three cultivars in 2023, with values of 87.3, 92.1, and 94.7% for ZD958, XY335, and LY99, respectively (Fig. 4).

3.3. Effects of different cultivars and growth phases on the RUE of maize

In this study, maize RUE was estimated using the regression slope between cumulative biomass and intercepted APAR (Lindquist *et al.* 2005; Ceotto *et al.* 2013). The observed cumulative biomass and APAR data were pooled to obtain a composite maize RUE of 5.71 g MJ^{-1} APAR during the entire growing season for the three study maize cultivars in both study years. Specifically, maize RUE values during the entire growing season were 5.85, 5.64, and 5.07 g MJ^{-1} for ZD958, XY335, and LY99, respectively (Fig. 5). The crop RUE changes over time as the plant grows (Muchow and Davis 1988; Cirilo and Andrade 1994; Shi *et al.* 2022). Maize RUE was higher during the vegetative phase than the reproductive phase, with composites of 6.85 and 5.64 g MJ^{-1} APAR, respectively, for the three study cultivars in the two study years (Fig. 6-A and B). The radiation intercepted by the canopy cannot be fully utilized during photosynthesis. According to the measured IPAR and APAR during the growing season for the three cultivars, the leaves absorbed 96.7 and 95.2% of IPAR in 2021 and 2023, respectively (Fig. 6-C and D).

4. Discussion

4.1. Limiting factors for maize RUE

Maize is widely cultivated globally; however, RUE varies greatly among different maize-growing regions due to

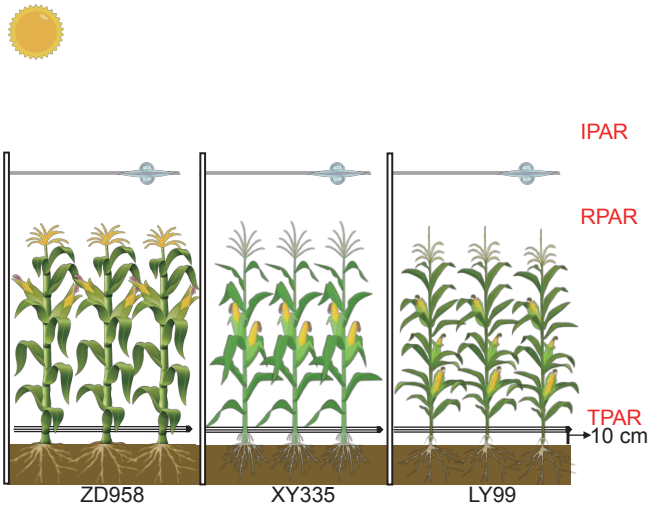


Fig. 2 Schematic diagram of photosynthetically active radiation (PAR) measurements for intercepted PAR (IPAR), reflected PAR (RPAR), and transmitted PAR (TPAR) for the three maize cultivars.

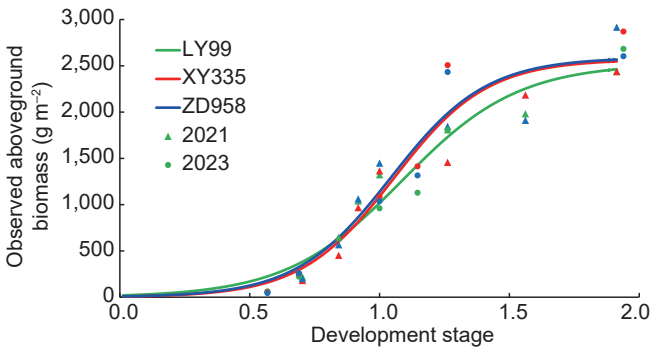


Fig. 3 Changes in the observed aboveground biomass during the developmental stages of three high-density maize cultivars in 2021 and 2023 at the study site. 0, emergence; 1.0, anthesis; 2.0, physiological maturity.

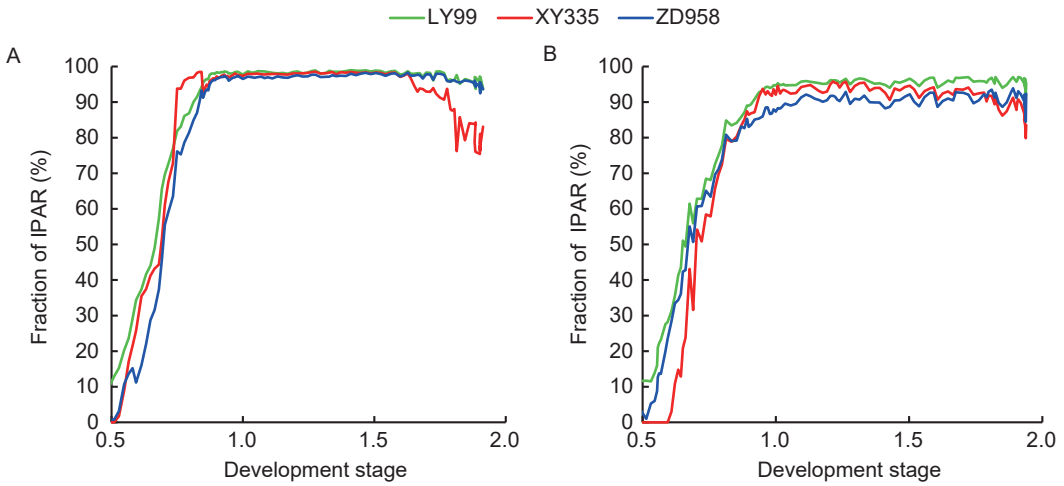


Fig. 4 Changes in the fraction of incident photosynthetically active radiation (IPAR) *vs.* the developmental stages of the three maize cultivars in 2021 (A) and 2023 (B). 0, emergence; 1.0, anthesis; 2.0, physiological maturity.

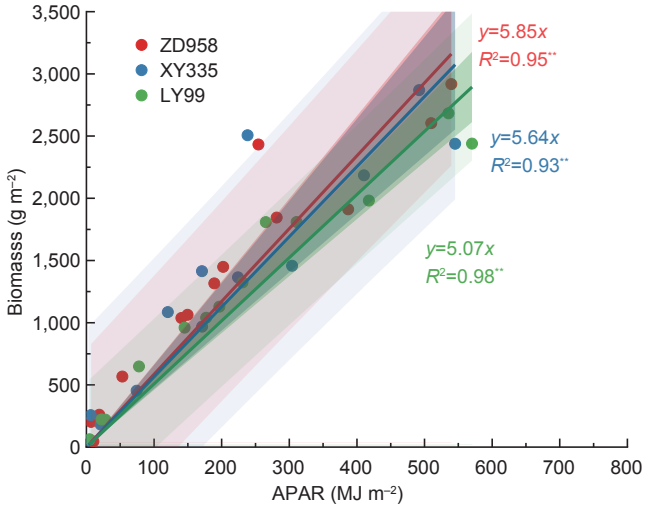


Fig. 5 Scatterplots of cumulative aboveground biomass *vs.* cumulative absorbed photosynthetically active radiation (APAR) from emergence to the target stages for the three maize varieties in 2021 and 2023. Each equation indicates the regression slope between cumulative biomass and APAR, with a suppressed intercept (since the intercept did not differ from zero). **, $P<0.01$.

climatic conditions (Shi *et al.* 2022). In China, previous scholars have often multiplied total solar radiation by 0.5 to estimate PAR (Sinclair and Muchow 1999), as reported in the studies published between 2009 and 2020. In this study, the observed PAR was used to calculate maize RUE and compare our results with other related studies.

According to previous field experiment studies in China, the maize RUE ranged from 1.28 to 5.74 g MJ^{-1} APAR (Fig. 7). The highest maize RUE was from the compact cultivar Denghai 618 planted at a high density of 9.8 plants m^{-2} (Wei *et al.* 2017). The maximum maize RUE for closed canopy interception of PAR was 5.50 g MJ^{-1} APAR (Loomis and Amthor 1999), and the upper limit of maize RUE was previously reported as 5.71 g MJ^{-1} APAR. In this study, the compact cultivar had the highest RUE (2.95 g MJ^{-1} APAR), followed by the semi-compact cultivar (2.72 g MJ^{-1} APAR) and then the horizontal-leaf cultivar (2.09 g MJ^{-1} APAR). The maximum aboveground biomass for the three cultivars was 2,917 g m^{-2}, which was more than the aboveground biomass at maturity for the maize RUE of 5.74 g MJ^{-1} APAR (2,587 g m^{-2}) (Wei *et al.* 2017). In addition to the influence of local radiation conditions, RUE is also closely related to planting density, plant type, irrigation and fertilization, especially the influence of plant type on light interception. In the future, we can also improve the RUE of maize, increase crop biomass accumulation and increase crop yield through improvements in the plant variety type.

4.2. Biomass accumulation is affected by RUE and PAR

For the three cultivars, IPAR gradually increased over time before anthesis (DVS<1.0), but remained constant at more than 90% of the peak value after anthesis (1.0<DVS<2.0). This is consistent with a previous related study (Liu X *et al.* 2023). In 2021, IPAR in the canopy of the semi-compact maize cultivar drastically decreased after DVS>1.6 due to the severe lodging. As a result, the IPAR for the horizontal-leaf maize was higher than that for the semi-compact maize. However, dry matter accumulation is affected by both IPAR and RUE (Liu X *et al.* 2017), and the semi-compact maize still had a higher biomass accumulation than the horizontal-leaf maize. For the three cultivars, RUE was higher during the vegetative phase than the reproductive phase, with averages of 6.85 and 5.64 g Mg^{-1} APAR, respectively. These results are consistent with the findings from previous related studies (Kiniry *et al.* 1989; Shi *et al.* 2022).

4.3. The RUE parameter in maize modeling

In current maize models, such as APSIM-Maize, RUE is set to 3.60 g MJ^{-1} APAR (Keating *et al.* 2003), which is not ideal for simulating maize yield under optimal growth conditions with high density planting. In Jilin Province, China, when using a maize model to simulate maize yield (especially the potential

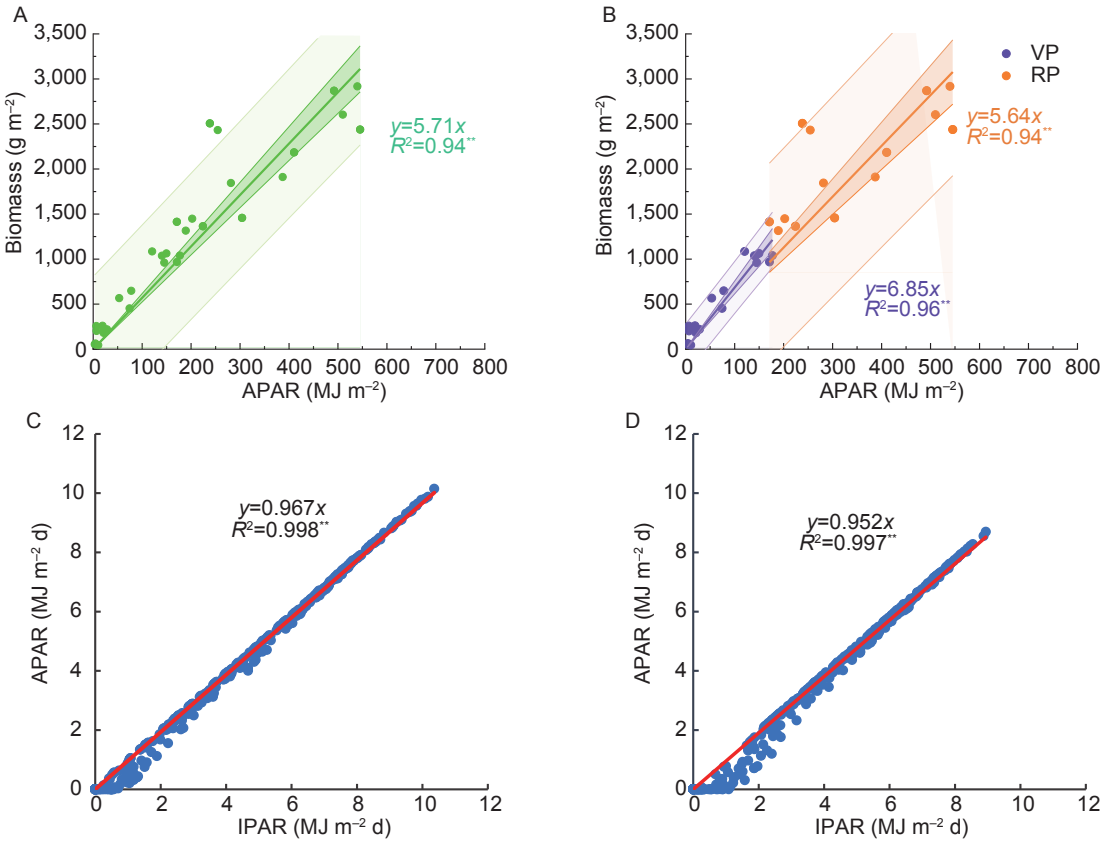


Fig. 6 Fitted relationships in 2021 and 2023. A and B, cumulative aboveground biomass *vs*. cumulative absorbed photosynthetically active radiation (APAR) from emergence to the target stages during the entire growing season (A) and the vegetative and reproductive phases (B) for the three maize cultivars in 2021 and 2023. VP, vegetative phase; RP, reproductive phase. C and D, APAR *vs*. incident photosynthetically active radiation (IPAR) from emergence to the target stages for the three maize cultivars in 2021 (C) and 2023 (D). The slope of each regression indicates the radiation use efficiency (RUE) value as the regression intercepts were all forced to zero.

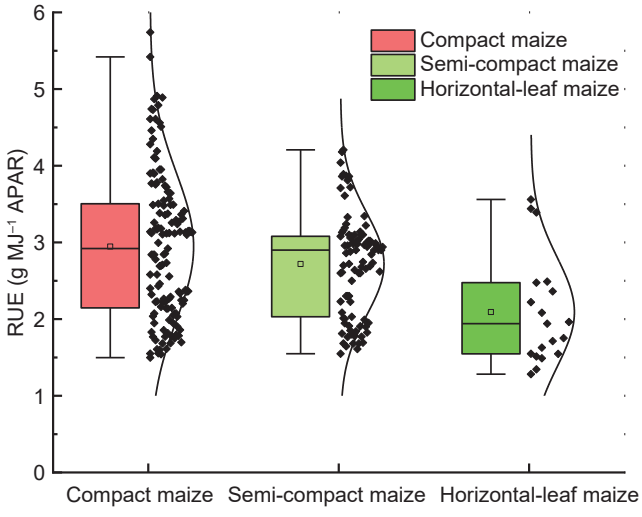


Fig. 7 Maize radiation use efficiency (RUE) for different cultivars reported in related studies from 2009 to 2020 (*n*=249).

yield), we suggest setting the RUE to 5.85, 5.64, and 5.07 g MJ^{-1} APAR for compact, semi-compact, and horizontal-leaf cultivars, respectively. Furthermore, the RUE parameter should be set to different values during the vegetative and reproductive phases.

5. Conclusion

The current high yield technology of high-density drip irrigation is mainly used to increase the biomass accumulation by increasing the RUE of the canopy. Based on this field experiment, we concluded that compact cultivars have better absorption of solar radiation than semi-compact and horizontal-leaf cultivars under optimal high density growth conditions. For the three maize cultivars in Jilin Province, China, ZD958 showed the highest RUE during the entire growth period (5.85 g MJ^{-1} APAR), followed by XY335 (5.64 g MJ^{-1} APAR), and then LY99 (5.07 g MJ^{-1} APAR). In general, maize RUE was higher during the vegetative phase than the reproductive phase, with averages of 6.85 and 5.64 g MJ^{-1} APAR, respectively, for the three study cultivars.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that they did not use AI in the preparation and writing of this manuscript.

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