**Canopy reflectance in two castor bean varieties (Ricinus communis L.) for growth assessment and yield prediction on coastal saline land of Yancheng District, China**

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**A B S T R A C T**

A field experiment was conducted in 2007–2009 in coastal saline regions of Yancheng city in Jiangsu province of China (120° 13′E, 33° 38′N). The experiment was to investigate relationships among canopy spectral reflectance, canopy chlorophyll density (CCD), leaf area index (LAI), and yield of two Chinese castor varieties (Zi Bi var. and Yun Bi var.) across four N fertilizer rates of 0, 90, 180, and 360 kg N ha\(^{-1}\). These N rates were used to generate a wide range of difference in canopy structure and seed yield. Measurements of canopy reflectance were made throughout the growing season using a hand-held spectroradiometer. Samples for CCD and LAI were obtained on days that reflectance measurements were made. Fifteen hyperspectral reflectance indices were calculated. Canopy spectral characteristics were heavily influenced by saline soil background in the rapid growing period (RGP), thus hyperspectral data obtained in this period were not suited for reflecting castor growth condition or predicting final yield. CCD increased linearly with most reflectance indices in the full coverage period (FCP) and senescent period (SP) for the two castor varieties, whereas LAI did not. Most of reflectance indices were significantly correlated with yield of two varieties in different growing periods. The OSAVI model provided the best yield prediction for Zi Bi var. with predicted values very close to observed ones (\(R^2 = 0.799\)), and the mSRVI705 model was well used for Yun Bi var. yield estimation (\(R^2 = 0.759\)). These results indicate that the hyperspectral data measured at appropriate time could be well used for castor yield estimation.

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1. Introduction

In recent years, castor plantations on coastal saline land have emerged in China to satisfy the need of castor oil, at the same time avoiding competition for food production (Li et al., 2010). However, infertile saline soil of coastal wetland has negative effects on castor plantation. For example, insufficient nitrogen (N) in coastal saline land does not benefit castor growth, while excessive use of N fertilizer not only increases production cost but also causes potential environmental problems (Oplinger et al., 1990). Therefore, nitrogen (N) management is one of the important practices in high-yielding castor production systems (Baldwin and Cossar, 2009). Moreover, the yield of castor seeds may fluctuate dramatically due to adverse climate in coastal areas. For above reasons, it is necessary to assess castor growth status timely and precisely to achieve high yield production.

Many studies indicated that remotely sensed data are useful tools to assess plant nutrient status (Baker and Rosenqvist, 2004; Dobrowski et al., 2005) and estimate plant growth and yields (Zhao et al., 2007; Harris, 2008). Nitrogen supply directly or indirectly affects chlorophyll content, LAI, canopy coverage, and other biophysical parameters, which may result in changes in spectral reflectance characteristics (Serrano et al., 2000). Both foliage and canopy spectral properties were found to be responsive to plant growth parameters like leaf chlorophyll content, leaf area index (LAI) and biomass which induced by different nitrogen treatments (Blackmer et al., 1996; Daughtry et al., 2000). For decades, hyperspectral reflectance indices, such as normalized difference vegetation index (NDVI), ratio vegetation index (RVI), chlorophyll absorption reflectance index (CARI), optimized soil-adjusted vegetation index (OSAVI), have been successfully used to assess plant LAI, biomass production and crop economic yields. Since yield is correlated with the amount of photosynthetic tissue which could be reflected by canopy chlorophyll density (CCD) or LAI, proper canopy reflectance indices that have significant relationships with CCD or LAI could be selected to predict crop condition and yield at early- and mid-growing season. Although numerous reflectance indices have been developed from canopy level on various plants, limited information is available in determining whether these hyperspectral reflectance indices can be used to assess castor growth and yield parameters. Furthermore, few studies dealing
with castor plantation on coastal saline land with castor canopy reflectance characteristics including both canopy growth and saline soil reflectance information were reported.

This study explores characterization on canopy reflectance and biomass and partition for two Chinese castor varieties on coastal saline land across different N treatments. Specific objectives are to: (1) characterize two castor varieties' performance in their different growing stages via canopy spectral reflectance, (2) determine relationships between selected reflectance indices and CCD, LAI and yield across different N fertilizer rates, and (3) establish primary castor yield prediction models by use of reflectance indices on coastal saline land. Our results provide new approaches for predicting castor growth and yield parameters on coastal saline land and, therefore, the soil contribution to spectral signals was significant, (2) the full coverage period (FCP, the middle stage when the canopy reached about 90% of ground cover), and (3) the senescent period (SP, the late stage when some castor seeds were mature and a few leaves became senescent). Corresponding to these growing periods, the spectral and agronomic sampling dates were 10 June, 28 July, 7 October (2007), 15 June, 30 July, 10 October (2008) and 23 June, 5 August and 16 October (2009). The harvest dates were 25 November (2007), 20 November (2008) and 5 December (2009), and oil seed that threshed seedcase was measured for seed yield.

2. Materials and methods

2.1. Experimental design and treatments

The experiment was conducted in the 2007, 2008 and 2009 growing seasons in coastal saline regions of Yancheng city which lies at 119°59′–120°33′E, 32°24′–34°07′N in north Jiangsu, China. The annual mean temperature is 13.8 °C, the monthly temperature in January and July is 0.8–28.8 °C, respectively. The annual mean precipitation is 960–1200 mm. It has no frost of 220 days and average annual total radiation of 2145 h. The main soil type is sullage-puddle soil, with total N of 0.04–0.07%, total P of 0.01–0.03%, total K of 0.8–1.5%, organic matter of 0.5–1%, and salinity of 0.1–0.5%. The experimental sites in three years were independent. Two Chinese castor varieties e.g. “Zi Bi” and “Ynu Bi” were used as trial materials. The variety of “Zi Bi” is known for its strong drought, chilling, and salt tolerance, and is planted mainly in Hebei, Henan and Hubei provinces (located at 30°–37°N). The variety of “Ynu Bi” has strong growth vigor, drought and salt tolerance, and its major planting area is in provinces of Guizhou, Yunnan and Sichuan (located at 23°–28°N). First, a similar parallel randomized experiment containing five replications was conducted in both castor varieties fields in 2009. Treatments were computed (Table 1). Although there are many spectral vegetation indices available, we selected a set of most commonly used ones for comparison analysis.

### Table 1

<table>
<thead>
<tr>
<th>Vegetation indices</th>
<th>Defined formulations</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRI</td>
<td>((R_{531} - R_{580})/(R_{531} + R_{580}))</td>
<td>Gamon et al. (1992)</td>
</tr>
<tr>
<td>NDVI</td>
<td>((R_{645} - R_{670}/R_{645} + R_{670}))</td>
<td>Rouse et al. (1974)</td>
</tr>
<tr>
<td>Green-NDVI</td>
<td>((R_{500} - R_{680})/(R_{500} + R_{680}))</td>
<td>Gitelson and Mezliyak (1996)</td>
</tr>
<tr>
<td>SIFI</td>
<td>((R_{670} - R_{450})/(R_{670} + R_{450}))</td>
<td>Penuelas et al. (1995)</td>
</tr>
<tr>
<td>RVI</td>
<td>((R_{450} + R_{500})/R_{500})</td>
<td>Rouse et al. (1974)</td>
</tr>
<tr>
<td>EVI</td>
<td>(2.5 \times (R_{660} - R_{570})/(R_{660} + 6 \times R_{570} - 7.5 \times R_{480} + 1))</td>
<td>Huete et al. (2002)</td>
</tr>
<tr>
<td>WI</td>
<td>(R_{660}/R_{570})</td>
<td>Penuelas et al. (1997)</td>
</tr>
<tr>
<td>DD</td>
<td>((R_{500} - R_{570}) - (R_{645} - R_{650}))</td>
<td>Le Maire et al. (2004)</td>
</tr>
<tr>
<td>WDRVI</td>
<td>((0.2 \times R_{660} - R_{570})/(0.2 \times R_{680} + R_{670}))</td>
<td>Gitelson et al. (2002)</td>
</tr>
<tr>
<td>PRI1</td>
<td>((R_{660} - R_{570})/(R_{660} + R_{570}))</td>
<td>Merzlyak et al. (1999)</td>
</tr>
<tr>
<td>OSAVI</td>
<td>(1.16 \times (R_{660} - R_{570})/(R_{660} + R_{570} + 0.86))</td>
<td>Daughtry et al. (2000)</td>
</tr>
<tr>
<td>mNDVI705</td>
<td>((R_{500} - R_{570})/(R_{500} + R_{570} - 2045))</td>
<td>Sims and Gannon (2002)</td>
</tr>
<tr>
<td>mSRVI705</td>
<td>((R_{500} - R_{570})/(R_{500} + R_{570}))</td>
<td>Sims and Gannon (2002)</td>
</tr>
<tr>
<td>R750R700</td>
<td>(R_{750}/R_{700})</td>
<td>Gitelson and Mezliyak (1996)</td>
</tr>
<tr>
<td>VARI-green</td>
<td>((R_{555} - R_{660})/(R_{555} + R_{660} - R_{680}))</td>
<td>Gitelson et al. (2002)</td>
</tr>
</tbody>
</table>

\(R_i = \) reflectance at wavelength \(\lambda\).
2.3. Biomass and partition

Four castor plants of both varieties were harvested on days after the canopy spectral and fluorescence measurements were made. Each plant was transported to the laboratory and then separated into leaves, branches, and stems and then weighed for leaf biomass calculations (g/m²). The green leaves from four plants were measured with a leaf area meter (CI-203, CID) to estimate

![Figure 1](image-url)

**Fig. 1.** (a) Canopy chlorophyll density (CCD) and leaf area index (LAI) for Zi Bi var. in three growing periods of 2007, 2008 and 2009 as affected by N treatments. Different letters express significantly different results among salinities at the 0.05 level. Values represent the means of five replicate. Values are presented as mean ± standard error of five replicates. (b) Canopy chlorophyll density (CCD) and leaf area index (LAI) for Yun Bi var. in three growing periods of 2007, 2008 and 2009 as affected by N treatments. (c) Yield for Zi Bi var. and Yun Bi var. in three growing periods of 2007, 2008 and 2009 as affected by N treatments.
the total leaf area per sample plot. Plant tissues were dried in a forced-air oven at 70 °C for 72 h and weighed. Values for LAI were further calculated from these laboratory measurements. Chlorophyll concentrations were determined according to Holm (1954) using a spectrophotometer (Uvikon 930). Canopy chlorophyll density (CCD) was computed by multiplying chlorophyll content by total leaf weights.

2.4. Data analysis

Reflectance values in 400–1200 nm were omitted from data analysis and 20 reflectance indices were computed (Table 1). One-way ANOVA was used to test for variations in N fertilizer levels for the following measurements: CCD, LAI, canopy reflectance and yield. Significant differences between CCD, LAI and yield were

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Fig. 2. (a) Canopy reflectance measurements on Zi Bi var. across four N rates in 2007, 2008, and 2009. (b) Canopy reflectance measurements on Yun Bi var. across four N rates in 2007, 2008, and 2009.
determined by Duncan’s multiple-range test. Pearson correlation coefficients (R) were calculated between CCD, LAI and yield in three growing periods using linear regression equations. Best growth stage for collecting canopy reflectance for yield estimation was determined based on the $R^2$ values of the linear regression equations.

3. Results

3.1. CCD, LAI and yield

The results of this study showed that both LAI and CCD increased rapidly as plants progressed through the rapid growing period and the full coverage period, and then decreased to some extent in the senescent period (Fig. 1). Meanwhile, both LAI and CCD increased significantly with respect to N treatments in the three periods. However, differences between the two varieties were observed in the three growing periods. CCD and LAI of Zi Bi var. were higher than Yun Bi var. in the rapid growing period whereas lower in the following growing periods provided with corresponding N rates. Yield of two castor varieties significantly correlated with N rates. Higher castor yields were obtained with more N inputs.

3.2. Canopy level reflectance measurements

All canopy spectra show two reflectance peaks at NIR (NIR) wavelength ranges (900–1000 nm and 1050–1200 nm, respectively). Both absorption in plant internal water and scattered reflection in canopy structure contribute to above spectral characteristics. Furthermore, significant increments at CCD (750–1100 nm) wavelengths were observed along with higher N treatments in three growing periods. Canopy reflectance spectrum for Yun Bi var. in the rapid growing period was much lower than the other two periods, especially in the visible (450–700 nm) and NIR (760–900 nm) wavelength ranges. This is mainly due to small LAI in this period that leads to low levels of vegetation cover and the canopy spectra are strongly influenced by the spectral properties of the background soil (Fig. 2).

3.3. Relationships between CCD, LAI and yield

CCD were significantly correlated with yield at 0.01 levels for two castor varieties in RGP and SP, whereas the linear regression coefficients ($R^2$) were lower when considering the two varieties as a whole than single ones (Table 2). LAI were significantly correlated with yield at 0.01 levels for two castor varieties throughout the growing periods, and the values of $R^2$ were also lower without considering variety differences. Thus, both CCD and LAI were good parameters for indicating castor yield when considering special castor varieties solely.

| Table 2 |
|-----------------|-----------------|-----------------|-----------------|
| BPs            | Growing periods | Zi Bi Var.      | Yun Bi Var.     | Both of varieties |
|----------------|-----------------|-----------------|-----------------|
| CCD            | RGP 0.587**     | 0.872**         | 0.464**         |
|                | FCP 0.387       | 0.156           | 0.113           |
| LAI            | RGP 0.666**     | 0.544**         | 0.301**         |
|                | FCP 0.536**     | 0.668**         | 0.305**         |

3.4. Relationships between CCD and LAI and VIs

Most indices increased linearly with the increase in CCD in the full coverage period and senescent period except WI, TVI and VARI-green indices for the two castor varieties. CCD, TVIBI, and DD showed strong linear associations with CCD ($R^2$ = 0.70–0.76). Many indices including PRI, PSRI, WI, TVIBI, EVI, mSRVI705, R750R700, VARI-green did not respond to increase in LAI for the two castor varieties. Furthermore, DD showed strong linear associations with CCD ($R^2$ = 0.589, 0.872, 0.464**). Both absorption in plant internal water and scattered reflection in canopy structure contribute to above spectral characteristics. Furthermore, significant increments at CCD (750–1100 nm) wavelengths were observed along with higher N treatments in three growing periods. Canopy reflectance spectrum for Yun Bi var. in the rapid growing period was much lower than the other two periods, especially in the visible (450–700 nm) and NIR (760–900 nm) wavelength ranges. This is mainly due to small LAI in this period that leads to low levels of vegetation cover and the canopy spectra are strongly influenced by the spectral properties of the background soil (Fig. 2).

3.4. Relationships between CCD and LAI and VIs

The regression equation parameters and $R^2$ values of castor Yun Bi var. yield and NDVI, PRI, Green-NDVI, SIPI, EVI, WDRVI, OSAVI or VARI-green generated in FCP and SP were shown in Table 3. Most of above VIs were highly significant correlated with yield in FCP ($R^2$ = 0.70–0.76). The OSAVI model was suitable to Zi Bi var. yield prediction in both FCP and SP, which were $Y = -0.82 + 4.74X (R^2 = 0.5996, FCP)$ and $Y = 0.03 + 4.32X (R^2 = 0.641, SP)$, respectively.

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3.5. The model of yield prediction

The regression equation parameters and $R^2$ values of castor Yun Bi var. yield and NDVI, PRI, Green-NDVI, SIPI, EVI, WDRVI, OSAVI or VARI-green generated in FCP and SP were shown in Table 3. Most of above VIs were highly significant correlated with yield in FCP ($R^2$ = 0.70–0.76). The OSAVI model was suitable to Zi Bi var. yield prediction in both FCP and SP, which were $Y = -0.82 + 4.74X (R^2 = 0.5996, FCP)$ and $Y = 0.03 + 4.32X (R^2 = 0.641, SP)$, respectively.

In order to test the feasibility of the linear models for yield estimation, the equations were used to predict yield of individual plots. Parallel N and P treatment plots were used to compare predicted and measured yields (Fig. 4). Among the above reflectance index
Fig. 3. (a) $R^2$ values of the linear relationship between CCD and VIs in FCP and SP growing seasons for two varieties. (b) $R^2$ values of the linear relationship between LAI and VIs in FCP and SP growing seasons for two varieties.

Fig. 4. Relationship between measured and predicted yield in (A) Zi Bi var. and (B) Yun Bi var. using linear regression models developed in 2007, 2008 and 2009 with OSAVI, Green-NDVI, mSRV1705 and PRI. The $R^2$ and root-mean-square error (RMSE) values are also presented.
models, the OSAVI model in SP provided the best yield prediction for Zi Bi var. \( R^2 = 0.799 \) with a root-mean-square error (RMSE) of 6.52%. The Green-NDVI model could be used to predict yield of Zi Bi var. in FCP with moderate success \( R^2 = 0.626, \text{RMSE} = 8.73\% \). The mSRVI705 and PRI models in SP could be well used for Yun Bi var. yield estimation \( R^2 = 0.759, R^2 = 0.698, \) respectively with RMSE of 5.60\% and 7.18\% respectively.

4. Discussion

4.1. Several important variables for castor growth assessment and yield prediction

Many reflectance variables have been successfully used for plant growth assessment and yield prediction. In this study, the reflectance values increased with the increments of N rates at NIR wavelength ranges. And the higher of reflectance values at NIR, the higher of seed yields. This is in agreement with many researches on other crops (Serrano et al., 2000; Gitelson, 2004; Zhao et al., 2007). However, castor was at low levels of vegetation cover in seedling period, thus canopy spectral characteristics were heavily influenced by the spectral properties of the background soil in this period, not suitable for castor growth assessment and yield estimation. When these data were removed, the correlation between VIs generated from canopy spectral wavelength and agricultural variables were significantly improved.

Besides choosing the proper period, the selection of the optimum agricultural variables can also benefit both the prediction accuracy of hyperspectral data and their ability to characterize crop developmental status (Wu et al., 2000). Canopy structure (LAI) and pigment (CCD) are two of the most important variables characterizing a canopy’s state (Blackburn, 1998). In many cases, canopy pigments, including chlorophylls and carotenoids, are closely and linearly related to most spectral indices (Jago et al., 1999; Hansen and Schjoerring, 2003). Our results showed that CCD performed similar relationships with different VIs, with higher \( R^2 \) values than LAI. The greenness of plant canopy was in saturation when LAI reached a certain value, and thereafter VIs would not increase in line with LAI increments. Therefore, CCD containing both the structure and pigment information of crops is very useful in characterizing castor developmental status in relation to hyperspectral VIs.

4.2. About the model of yield prediction

Our results suggest that proper selection of both measuring date and hyperspectral VIs is important for precisely predicting castor yield. It is evident that blooming stage for Zi Bi var. and early fruiting stage for Yun Bi var. were the best time for measuring canopy reflectance in order to accurately estimate yield. The poor relationship between yield and most reflectance indices, calculated from reflectance data collected at seedling stages in this paper, was probably associated with a low LAI. Zhao et al. (2007) also reported a weak correlation between yield and RVI or NDVI in cotton when LAI was low. As castor grew throughout reproductive stages, the LAI increased and the canopy also became gradually mature and stable. Thus VIs observed in these stages would be well suited for yield estimation. Similar results were documented on soybean (Ma et al., 2001) and winter wheat (Moges et al., 2004). However, the relationships of soybean seed and wheat grain yields with VI (NDVI) followed a power or exponential function rather than the linear function. Our results indicated that Zi Bi var. yield was associated with NDVI, Green-NDVI, RVI, EVI, WDRVI, and OSAVI at blooming stage with \( R^2 \) around 0.58 \((P < 0.01)\), and Yun Bi var. yield was associated with PRI, Green-NDVI, SII, PSRI, mNDVI705, and mSRVI705 at flowering stage with \( R^2 \) from 0.53 to 0.83 \((P < 0.01)\). Therefore, these canopy reflectance indices and linear algorithms developed around reproductive stage may be used to predict final yields of different castor varieties. Additionally, validation of the regression models (Fig. 4) suggested that the performance of the OSAVI model of Zi Bi var. and the mSRVI705 model of Yun Bi var. were better than that of other models for castor yield prediction.

5. Conclusion

Hyperspectral remote sensing combined with important biophysical parameters (CCD and LAI) were successful in castor growth assessment and yield prediction on coastal saline land. The coefficients of the linear regression models between yield and the reflectance indices indicated that blooming stage in Zi Bi var. and fruiting stage in Yun Bi var. were the best time to measure canopy reflectance for prediction of seed yield. Most tested canopy reflectance indices may be used to determine canopy structure status, to assess yield, and to help researchers and farmers make field management decisions during the growing season. Thus, high seed yield could be achieved. Furthermore, castor yield was influenced by many environmental factors, such as light irradiation, temperature, precipitation, and soil salinity dynamics. Further research on castor yield prediction models considering yearly environmental variation on coastal saline land is necessary to improve the accuracy of models.

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