Estimation of wheat traits using radiative transfer models and artificial neural network

1. Reflectance model

PROSAIL model: PROSAIL is the combination of PROSPECT (a leaf optical property model) and SAIL (a canopy bidirectional reflectance model). It links the spectral variation of canopy reflectance (mainly related to leaf biochemical contents) with its directional variation (primarily related to canopy architecture and soil/vegetation contrast) which is key to simultaneous estimation of canopy biophysical/structural variables for applications in agriculture, plant physiology, or ecology, at different scale (Jacquemoud et al., 2009).

Both input and output variables are presented in Table 1. The soil properties are computed based on the mix of a dry soil and a wet soil. The soil reflectance (rsoil) is computed as:

rsoil0 = psoil\*Rsoil1+(1-psoil)\*Rsoil2

where psoil represents a ratio used to mix a dry soil and a wet soil, based on the hypothese that soils in general could be represented by such mixed spectrum; Rsoil1 and Rsoil2 are the reflectance property of dry and wet soil, respectively. The actual situation is not the case, but this is just a simplified way to illustrate the possibility to adjust soil properties in a continuous fashion.

Table 1 Description of input and output variables of PROSAIL model

|  |  |
| --- | --- |
| Variables | PRO4SAIL |
| Input | **Solar-object-sensor geometry:**   * , solar zenith angle (deg) * , viewing zenith angle (deg) * , relative azimuth angle (deg)   **Leaf properties:**   * N, leaf mesophyll structure parameter ( a leaf is assumed to be composed of a pile of N homogeneous layers separated by N-1 air spaces.) * Cw, leaf water content or leaf equivalent water thickness (cm) * Cm, leaf dry matter content (g cm-2) * Cab, leaf chlorophyll-a and -b content (µg cm-2) * Car, carotenoid content (µg cm-2) * Cant, anthocyanins content (µg cm-2) * Cbrown, brown pigment content or fraction of brown leaves   **Soil properties:**   * *rsoil*, soil’s reflectance   **canopy architecture:**   * LAI, leaf area index (m2 m-2) * LIDF, leaf inclination density function   (TypeLidf=1, parameter a, b;  TypeLidf=2, Parameter ALA)   * *q*, hot-spot size parameter (m m-2) |
| Output | * resv, directional reflectance of canopy |

1. Synthetic dataset

The reflectance of synthetic dataset is computed by running the PROSAIL model in the forward direction with the values of input variables as described in Table 2. The maximum and minimum values of the parameters were fixed based on field data collection and empirical knowledge.

Table 2 Details of input variables of experimental plan used to simulate the synthetic dataset with PROSAIL model

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Variables | Distribution | Mean | SD | LB | UB | Values used in experiment |
|  | Uniform | - | - | 0 | 90 | 30, 60, 90 |
|  | Uniform | - | - | 0 | 90 | 0 |
|  | Uniform | - | - | -180 | 180 | 0, 180 |
| N | Gaussian |  |  |  |  |  |
| Cw | Gaussian |  |  |  |  |  |
| Cm | Gaussian |  |  |  |  |  |
| Cab | Gaussian |  |  |  |  |  |
| Car | Gaussian |  |  |  |  |  |
| Cant | Gaussian | - | - | - | - | 0 |
| Cbrown | Gaussian |  |  |  |  |  |
| *psoil* | Gaussian |  |  |  |  |  |
| LAI | Gaussian |  |  |  |  |  |
| ALA | Gaussian |  |  |  |  |  |
| *q* | Gaussian |  |  |  |  |  |

when solar dedication angle equals to latitude at 12:00 o’clock (太阳直射该地时的正午太阳高度角为90。日出和日落时的太阳高度角为0，同一地点一天内太阳高度角是不断变化的；日出日落前的太阳高度角小于0，在这里没有意义). can be determined according to the latitude of field location and UAV flight time.

The sensor carried on UAV captures orthographic images at nadir point where.

Relative azimuth angle (: RAA=VAA-SAA (VAA, sensor(view) azimuth angle; SAA, sun azimuth angle)

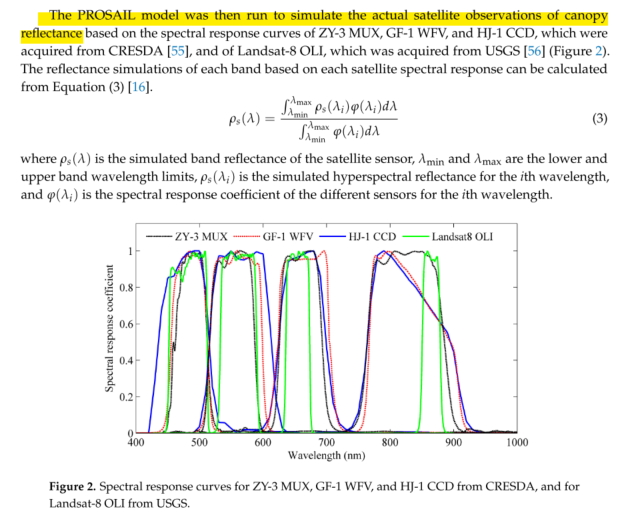
对于地球上任何位置，当太阳处于春分点或秋分点，即太阳赤纬是0°的时候，初升的太阳方位角是90°整，正午太阳方位角是180°，落日的时候太阳方位角是270°。对北半球而言，当太阳赤纬大于0°的时候太阳从东偏北方向升起，此时太阳方位角小于90°，中午180°，落日时太阳方位角大于270°。当太阳赤纬小于0°的时候太阳从东偏南方向升起，此时太阳方位角大于90°，中午180°，落日时太阳方位角小于270°。

Calculation of solar zenith angle, solar altitude angle and day length: “The Role of Solar-Radiation Climatology in the Design of Photovoltaic Systems”

<https://www.sciencedirect.com/topics/engineering/solar-incidence-angle>

We simulate reflectance for each wavelength from 400 to 2500 nm and then integrate them into corresponding bands of multispectral or hyperspectral images.

The reflectance of each band is calculated with a spectral response function (SRP) [or Relative Spectral Response (RSP)] as:



If there is no corresponding spectra response function, compute band reflectance with the following equation:

Input variables

* , solar zenith angle (deg)
* , viewing zenith angle (deg)
* , relative azimuth angle (deg)
* N, leaf structure parameter
* Cw, leaf water content or leaf equivalent water thickness (cm)
* Cm, leaf dry matter content (g cm-2)
* Cab, leaf chlorophyll-a and -b content (µg cm-2)
* Car, carotenoid content (µg cm-2)
* Cant, anthocyanins content (µg cm-2)
* Cbrown, brown pigment content or fraction of brown leaves
* *rsoil*, soil’s reflectance

( scaling factor to be multiplied with single soil reflectance spectrum;

scaling factor between two model-implemented soil spectra (wet versus dry))

* LAI, leaf area index (m2 m-2)
* LIDF, leaf inclination density function

(TypeLidf=1, parameter a, b;

TypeLidf=2, Parameter ALA (average leaf angle))

* *q*, hot-spot size parameter (m m-2)
* *skyl, the proportion of diffuse energy*

Notes: a – interval, b – expectation/common value, c – divisions/levels, KDE – kernel density estimation

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Variables | {Zhao, 2018 #73} | {Zou, 2018 #61} | {Zhu, 2018 #67} | {Zhang, 2018 #66} | {Punalekar, 2018 #58} | {Garcia-Haro, 2018 #63} | {Campos-Taberner, 2018 #62} |
| crop | maize | Faba bean, Narrow-leafed lupin, Turnip rape, Oat, Barley, Wheat | Maize, wheat | Vegetation | Herbs, grass | Vegetation | vegetation |
|  | 0-85(1a) | 49.4 | 23.12 | 0-90(30b) |  | - | - |
|  | 0-35(1a) | 9 | 9.78 | 0-90(0b) |  | - | - |
|  | - | 90 | 111.39 | 0-180(0b) |  | - | 0 |
| N | 1.518 | 1.55 | 1.4-2.2(1.6b) | 1-3(1.5b) | 1.6 | 1.2-2.2((N(1.5,0.32)) | 1.2-2.2(N(1.6,0.32)) |
| Cw | - | 0.001-0.02 | 0.01-0.04(0.02b) | 0.004-0.04(0.015b) |  | 0.6-0.85(N(0.75,0.12))? | KDE |
| Cm | 0.003663 | 0.005 | 0.001-0.01(0.008b) | 0.0019-0.0165(0.009b) |  | 0.005-0.03(N(0.015,0.0082)) | KDE |
| Cab | 40-60(10a) | 25-100 | 30-65(40b) | 0-100(50b) |  | 20-90((N(45,302)) | KDE |
| Car | 10 | 0.2\*Cab | - | 5-30(10) |  | 0.6-16(N(5,72)) | 0.6-16(N(5,72)) |
| Cant | - | - | - |  |  | - | - |
| Cbrown | 0.05 | 0 | - | 0 |  | 0 | 0 |
| */psoil* | - | - | (*psoil*) 0-1  (0.4b) | (*psoil*) 0-1  (0.1b) |  | (*psoil*) 0-1  (N(0.8,0.62)) | 0.1-1(N(0.8,0.62)) |
| LAI | 0-8(0.1a) | 1-5 | 0-5(1.5b) | 0-6(3.5b) |  | 0-8(N(3.5,42)) | 0-8(N(3.5,42)) |
| ALA | 40-70(10a) | 15-70 | 45-65(55b) | 0-90(50b) |  | 35-80((N(62,122)) | 35-80(N(60,122)) |
| *q* | 0.1 | 0.01 | 0-1.4 | 0-1(0.1b) | 0.05 | 0.1-0.5(N(0.2,0.22)) | 0.1-0.5(N(0.2,0.22)) |
| *Skyl* | - | - | - | 0-1(0.1b) |  | - | - |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Variables | {Li, 2018 #64} | {Danner, 2017 #77} | {Danner, 2019 #166} | {Zhang, 2016 #150}  {Guo, 2018 #167} | {Berger, 2018 #72} |  |
| crop | Winter wheat | Winter wheat | wheat | wheat | wheat |  |
|  | 25-70(46b) | 30-55(6c) |  | 30 |  |  |
|  | 0-80(32b) | -30-30(3c) |  | 0 |  |  |
|  | -120-120(90b) | 0-65(14c) |  | 0 |  |  |
| N | 1.2-1.8(N(1.5,0.32)) | 1-2.5 | 1.4-4.4 | 1.5 | 1-2.5 |  |
| Cw | 0.6-0.85(0.75b)? | 0.001-0.05 | 0.001-0.035 | 0.0184 | 0.001-0.05 |  |
| Cm | 0.003-0.011(N(0.007,0.0022) | 0.001-0.02 | 0.0031-0.0075 | From WheatGrow | 0.001-0.02 |  |
| Cab | 25-75(N(50,7.52)) | 0-80 | 11.6-59.5 | From WheatGrow | 0-80 |  |
| Car | - | 0-20 | - | 20 | 0-24 |  |
| Cant | - | - | - | - | - |  |
| Cbrown | 0-0.2(N(0,0.32)) | 0-1 | 0-1 | 0 | 0-1 |  |
| */psoil* | ()0.5-3.5(N(1.2,22)) | (*psoil*) 0-1 |  |  | (*psoil*) 0-1  ()0.5-2.2 |  |
| LAI | 0-8(5b) | 0-8 | 0.01-6.27 | From WheatGrow | 0-8 |  |
| ALA | - | 20-90 | 25-78 | 68.2 | 20-90 |  |
| *q* | 0.1-0.5(N(0.3,0.22)) | 0.01-0.5 |  | 0.2 | 0.01-0.5 |  |
| *Skyl* | 0.1 | 0.1-0.1 | Calculated from | 0.1 | 0.23 |  |

Notes:

a – interval, b – expectation/common value, c – divisions/levels, KDE – kernel density estimation

*/psoil* 与作物无关，受土壤组分属性影响

*Skyl*与作物无关，可根据太阳天顶角计算，计算理论参考François et al. (2002)（模型里有提及）

1. Artificial neural network

参数组合

波段反射率计算：针对哪个传感器（这个传感器有哪几个波段，具体每个波段的波中心波长及带宽）？

波段组合（隐含波段数目）

日期组合：结合phenotype及生产需要，一般在哪些日期进行数据采集？

ANN输入：波段反射率，不同波段反射率间关系（B1\*B2, r(B1,B2),VI指数)

1. Application of ANN