Spatiotemporal Assessment of Agricultural Drought Using a Cell-Based Daily Soil Water Analysis Model

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Abstract: This study developed a cell-based daily soil water analysis model (CellSW) for evaluating agricultural drought and calculated an agricultural drought index called the “Rainfall Effectiveness Index for Crop” (REIC). The model analyzed a daily soil water balance based on crop types, growth stages, soils, and climate. It adopted the rasterized daily rainfall, daily evapotranspiration, crop coefficient (by crop growth stage), and root depth as input parameters; it also consecutively generated the daily surface layers of the water balance items in each cell, such as the consumptive use, effective rainfall, available soil water, and irrigation requirements. The model was applied in a test area in Illinois and Iowa, targeting corn and soybeans; the soil water balance was analyzed during the growing period from 2000 to 2018. The model calculated the seasonal REIC, defined as the ratio of supply quantity (effective rainfall) to demand quantity (crop evapotranspiration). In addition, the accumulated REIC values were estimated. The REIC was confirmed to accurately reflect drought situations in the relevant areas, based on comparisons with drought records. The cell-based model can be applied to different types of cultivated crops, growth stages, and soil conditions without spatial and temporal limitations, even in mixed farming.

Keywords: soil water balance; cell; agricultural drought

1. Introduction

Drought is a natural disaster with a random nature, and it causes longer, wider, and greater damage than any other natural disaster. As drought proceeds over a long term unlike other natural disasters, its damage can be significantly mitigated if it is detected earlier, or even while in progress. Therefore, scientists have tried to establish drought countermeasures suitable for different regions, based on identifying the temporal characteristics and spatial distribution of the drought [1–5].

In general, drought refers to a state in which the required water cannot be supplied owing to a lack of precipitation; it is classified into meteorological or climatological, agricultural, hydrological, and socioeconomic drought [6]. Major droughts are defined as meteorological droughts and consist of a period of months to years with below-normal precipitation [7]. Agricultural drought can be defined by the influences of meteorological or hydrological droughts on agriculture—i.e., by characteristics such as a lack of precipitation, deficit of available soil moisture, or decrease in groundwater or reservoir levels. Soil moisture has been commonly used for the assessment of agricultural drought, as it not only adequately reflects the moisture stress of crops, but also precedes hydrological drought. Efforts to measure or estimate soil moisture have been very active.
Understanding the characteristics of soil moisture requires a lot of observational data. Observation data for soil moisture are accurate but require significant time and labor to cover a wide geographical area. For this reason, many studies have been carried out to evaluate agricultural drought severity using remote sensing data or soil moisture analysis models [8–17]. In the case of study using remote sensing data, the drought was evaluated using soil moisture, vegetation activity, and land surface temperature data, which are used to monitor agricultural droughts [8–12]. These studies have the advantage of overcoming the spatial limitation of ground observation data, but there are limitations such as image acquisition frequency, sensor-specific errors, and uncertainty of specific algorithms. For studies using the soil moisture analysis model, agricultural drought was evaluated by using meteorological data (precipitation and evapotranspiration), soil data (soil properties, field capacity, wilting point, and hydrological soil group), and farming data (cultivation period, crop coefficient, and root depth) as input data [14–17]. Their spatiotemporal distribution, however, has mostly been expressed very simply, as limited soil data were used or the soil moisture was estimated by assuming a single crop.

Several methodologies for drought characterization exist; however, using drought indices is prevalent [18]. More than 100 drought indices have so far been proposed to evaluate different types of drought severity, including meteorological, agricultural, and hydrological drought [19]. These drought indices have advantages and disadvantages for each indicator, so it is difficult to determine the superiority of a particular index. Therefore, an appropriate drought index must be applied according to the target or the purpose of analysis. Among the numerous drought indexes, the most popular are the Palmer Drought Severity Index (PDSI) [20] and Standardized Precipitation Index (SPI) [21], which are meteorological drought indices. The PDSI is calculated based on precipitation, temperature data, and the SPI is calculated based on precipitation data only. However, although the meteorological and hydrological drought index are not drought state, the agricultural drought index could be drought state. The agricultural drought index primarily used the Standardized Precipitation Evapotranspiration Index (SPEI) and Soil Moisture Index (SMI) [22–27]. The SPEI was developed for evaluating agricultural drought severity in consideration of meteorological and crop evapotranspiration [22–25]. The SMI is computed based on the soil characteristics and soil moisture conditions and the parameters include field capacity, wilting point, and soil moisture [26,27]. The SPEI is calculated including crop growth data, but soil data are excluded. In contrast, The SMI is calculated including soil data, but crop growth data are excluded. The agricultural drought index needs to be calculated by including meteorological factors, soil characteristics, and crop growth. In particular, as each crop has different spatial distributions for cultivation, different cultivation periods, crop coefficients and root depths by growth stage, it is necessary to fully utilize their characteristics.

In addition, as agricultural water is used at different times in different forms, the drought recognized at agricultural sites can be different temporally and spatially, despite the occurrence of agricultural drought owing to the lack of precipitation [28]. In other words, identifying the temporal changes and spatial distribution is very important in the analysis of agricultural drought. Therefore, it is necessary to express the spatiotemporal distribution in various ways using the various soil and crop characteristics, and to overcome the limitations caused by targeting specific areas or sub-watersheds in terms of scale.

This study attempted to develop a cell-based soil water balance model for reflecting changes by period according to cultivated crops, growth stages, and soil conditions, and for estimating the soil moisture for mixed farming regardless of the spatial and temporal scale. Additionally, based on the results of the soil water balance, an agricultural drought index (Rainfall Effectiveness Index for Crop (REIC)) was calculated, and the progress and severity of the drought were analyzed.

2. Materials and Methods

The cell-based daily soil water analysis model (CellSW) consists of three stages: Input data collection and preprocessing, soil water modeling, and analysis of agricultural drought (Figure 1).
The input data consist of meteorological, soil, and crop data. All input data were processed using grid maps with the same coordinate system and spatial resolution (250 m). In the soil water modeling stage, grid maps and statistical data of the effective rainfall (ER), consumptive use (CU), irrigation requirement (IR), and water deficit (WD) were created through a continuous soil moisture analysis. Finally, the “Rainfall Effectiveness Index for Crop” (REIC, an agricultural drought index for field crops) was calculated, based on the relationship between the ER and actual crop evapotranspiration (ETa). Based on this, an attempt was made to investigate the spatiotemporal characteristics of the agricultural drought of field crops.

Figure 1. Procedure for cell-based daily soil water analysis modeling.

2.1. Cell-Based Daily Soil Water Analysis Model (CellSW)

In this study, the soil was considered as a single layer and was simplified by excluding the lateral inflow, runoff, and groundwater recharge effects under unsaturated conditions. For the water balance equation, the moisture capillary rise (CR) and leaching requirement (LR) were neglected, and the deep
where \( SM \) denotes the soil moisture (mm/day), \( PR \) denotes the precipitation (mm/day) in the case of more than 5.0 mm/day, \( ETa \) denotes the actual crop evapotranspiration (mm/day), as calculated by multiplying the Penman–Monteith reference evapotranspiration by the crop coefficient, \( RO \) denotes the surface runoff, and \( t \) denotes time.

![Schematic diagram of soil water balance model.](image)

**Figure 2.** Schematic diagram of soil water balance model.

The soil moisture analyzed using the water balance equation can be converted into the available moisture (AM) for growth between the field capacity (FC) and wilting point (WP) (Table 1). As the use of the AM is convenient in computer modeling, the water balance items were calculated using it (Table 2).

**Table 1.** Calculation of soil moisture (SM(t)).

| Condition                  | AM(t)   | RO(t)  | ER(t)   | WD(t)  |
|----------------------------|---------|--------|---------|--------|
| If \( SM(t) >= FC \)       | FC      | SM(t)-FC | PR(t)-RO(t) | 0      |
| Else if \( WP <= SM(t) < FC \) | SM(t)   | 0      | PR(t)   | 0      |
| Else if \( PWP * < SM(t) < WP \) | SM(t)   | 0      | PR(t)   | WP-SM(t) |
| Else                      | PWP     | 0      | PR(t)   | WP-PWP = 50% of TAM ** |

* PWP: permanent wilting point, ** TAM: total available moisture (TAM)

**Table 2.** Calculation of available soil moisture (AM(t)).

| Condition                  | AM(t)   | RO(t)   | ER(t)   | WD(t)  |
|----------------------------|---------|---------|---------|--------|
| If \( AM(t) >= RAM * \)     | RAM     | AM(t)-RAM | PR(t)-RO(t) | 0      |
| Else if \( 0 <= AM(t) < RAM \) | AM(t)   | 0      | PR(t)   | 0      |
| Else if \( RAM < AM(t) < 0 \) | AM(t)   | 0      | PR(t)   | AM(t)  |
| Else                      | RAM     | 0      | PR(t)   | RAM    |

* RAM: readily available moisture
2.2. Agricultural Drought Index

The agricultural drought index, assessing the lack of soil moisture, was calculated through a comparison between the water balance elements as analyzed by the developed soil water balance model. The water value actually used was the effective rainfall, as the soil water balance model does not consider irrigation. Decreased effective rainfall and increased crop evaporation are direct results of increased demand for agricultural water. Equation (3) defines the Rainfall Effectiveness Index for Crop (REIC), which represents the association between consumptive use (CU) and effective rainfall (ER). A higher REIC indicates favorable water balance conditions with an adequate environment for cultivating field crops. A lower REIC indicates unfavorable conditions for growing field crops and a higher sensitivity to agricultural drought [5].

\[ REIC = \frac{\sum ER}{\sum CU} \]  

where \( ER \) is the effective rainfall, and \( CU \) is the crop consumptive use which is defined as the sum of actual crop evapotranspiration (\( ET_a \)).

2.3. Data Collection and Preprocessing

2.3.1. Study Area

The model developed in this study was applied in Illinois and Iowa, located in the Midwestern United States. These two regions are the most important agricultural states in the United States, as they are the central states of the corn belt region, where corn is cultivated on a large scale. In addition to corn, various cultivars are also cultivated, including soybeans, wheat, sorghum, and oats.

2.3.2. Data Collection and Preprocessing

Daily meteorological data during a 19-year period (2000–2018) were used in this study. The data of daily precipitation, temperature (minimum, maximum, mean), mean wind speed, mean relative humidity, and solar radiation from 2000 to 2018 were downloaded from the data sharing network of the Illinois climate network and Iowa soil moisture network [29,30]. The reference crop evapotranspiration (\( ET_0 \)) was calculated using the Penman–Monteith equation recommended by the Food and Agriculture Organization of the United Nations (FAO) paper No. 56 [31] using the meteorological data collected. The FAO Penman–Monteith equation used for 24-h calculations of \( ET_0 \) using daily or monthly mean data can be simplified, and is expressed as Equation (4):

\[ ET_0 = \frac{0.408(R_n - G) + \gamma \left( \frac{900}{T + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)} \]  

where \( ET_0 \) is the reference crop evapotranspiration (mm/day), \( \Delta \) is the slope of the saturated vapor pressure/temperature curve (kPa/°C), \( \gamma \) the psychrometric constant (kPa/°C), \( u_2 \) the wind speed at a 2-m height (m/s), \( R_n \) the net radiation at the crop surface (MJ/m²-day), \( G \) the soil heat flux density (MJ/m²-day), \( T \) the mean daily air temperature at a 2-m height (°C), \( e_s \) is the saturation vapor pressure (kPa) and \( e_a \) is the actual vapor pressure (kPa).

As for the soil information, the effective moisture content was based on the organic matter content in the soil survey geographic database (SSURGO) of the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) [32]. As for the crop cultivation map, the cropland data layer (an annual crop classification map provided by the USDA) was used [33]. The cultivation period was set to 133 days (1 May to 10 September) for corn and 113 days (21 May to 10 September) for soybeans, based on examining the data for Illinois and Iowa published by the USDA [34–37]. The crop coefficients (Kc) presented by the researchers ranged from 0.25 to 1.30 for corn and 0.23 to 1.15 for beans, depending on the cultivation period and region. The Kc were determined
according to the crop growth stages, taking into account the cultivation period of the region [31,38–40]. Based on rooting characteristics data of the corn and soybeans by growth stage, the root depths were set for each crop growth stage [41–43] (Table 3).

| Table 3. Crop coefficients and root depth by growth stages. |
|------------------------------------------------------------|
| **Crop** | **Growth Stage** | **From** | **To** | **Length** | **Crop Coefficient** | **Root Depth(m)** |
|----------|-------------------|---------|-------|------------|----------------------|------------------|
| Corn     | Initial           | 1 May   | 31 May| 31 days    | 0.30                 | 0.3              |
|          | Developing        | 1 June  | 30 June| 30 days    | Linear               | 0.6              |
|          | Mid-season        | 1 July  | 10 August| 41 days    | 1.15                 | 0.9              |
|          | Late-season       | 11 August| 31 August| 21 days    | Linear               | 1.2              |
|          |                   |         |       |            |                      |                  |
|          |                   | 1 September| 10 September| 10 days    | 0.40                 | 1.2              |
| Soybean  | Initial           | 21 May  | 10 June| 21 days    | 0.40                 | 0.3              |
|          | Developing        | 11 June | 10 July| 30 days    | Linear               | 0.5              |
|          | Mid-season        | 11 July | 20 August| 41 days    | 1.15                 | 0.7              |
|          | Late-season       | 21 August| 31 August| 10 days    | Linear               | 0.9              |
|          |                   |         |       |            |                      |                  |
|          |                   | 1 September| 10 September| 10 days    | 0.35                 | 0.9              |

3. Results and Discussion

3.1. Change in Soil Water Balance from 2000 to 2018

The values of the consumptive use (CU), effective rainfall (ER), irrigation requirement (IR), and water deficit (WD) were analyzed from 2000 to 2018 using CellSW (Figures 3 and 4). When changes by period were examined over the past 19 years (2000–2018), the water balance was found to be the best in 2009 and 2010. In 2012 and 2017, however, poor water balance results were observed for both soybeans and corn in the two states, indicating that there could have been severe drought stress.

![Figure 3](image)

Figure 3. Results of annual water balance results (precipitation, consumptive use, effective rainfall, irrigation requirement, and water deficit) for corn and soybean in Illinois, USA.
Over the past 19 years (2000–2018), the CU was found to be 127% higher for corn and 137% higher for soybeans relative to the average annual precipitation. Although there were differences depending on the period and region, the CU was generally higher than the precipitation, except for in 2009 and 2010. Both states exhibited the highest CU in 2012. The lowest precipitation was observed in 2017. In particular, the average annual rainfall in Iowa for the past 19 years (2000–2018) was 43% (164 mm) for corn and 34% (107 mm) for soybeans. The lowest ER was observed in 2017 (as with precipitation), and the highest ER was observed in 2010.

The IR generally exhibited a pattern similar to the results of the analysis for CU. In 2012, when the IR was the largest, the IR increased to 116–133% relative to the average over the past 19 years. The IR was large in 2012 even though the precipitation and ER increased relative to 2017, when the precipitation and ER were extremely small. The WD is the water quantity that does not satisfy the CU and varied significantly depending on the period and region. The WD was analyzed and found to be very small in 2009 and 2010 when the CU, ER, and IR were all in excellent conditions, but was analyzed to be very large in 2005, 2006, 2012, and 2017, when all of them were in poor conditions.

3.2. Spatiotemporal Characterization of Agricultural Drought Using Rainfall Effectiveness Index for Crop (REIC)

The averages and standard deviations of the REIC from 2000 to 2018 were calculated based on the daily ER and CU results for corn and soybeans (Figures 5 and 6). The REIC was very high in 2009 for Illinois and in 2010 for Iowa, when the CU was relatively small and the ER was relatively large. In contrast, the REIC was very low in 2005 and 2017 for Illinois and in 2012 and 2017 for Iowa, when the CU was relatively large and the ER was relatively small.
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In contrast, the REIC was very low in 2005 and 2017 for Illinois and in 2012 and 2017 for Iowa, when the CU was relatively large and the ER was relatively small.

For many of the last 19 years (2000–2018), the REIC values for each crop were found to be lower in Iowa than in Illinois. This is because the annual PR and ER were smaller, and the CU was larger in Iowa than in Illinois. It is possible to directly identify the regional difference in the drought stress of the field crops through the spatiotemporal distribution of the REIC (Figure 7). The REIC was found to fluctuate due to time and regional differences but was similar (or at least not different) between the two crops.

Figure 5. Temporal and regional changes in the rainfall effectiveness index for crop (REIC) for corn and soybean in Illinois, USA.

Figure 6. Temporal and regional changes in the REIC for corn and soybean in Iowa, USA.
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Figure 7. Spatiotemporal distribution of agricultural drought using annual REIC.
3.3. Validating Indices Using U.S. Drought Monitor (USDM) Drought Records

Identifying drought characteristics through an analysis of the spatiotemporal distribution of agricultural drought is very important for establishing drought countermeasures. The above REIC values calculated by year make it easy to intuitively determine the drought years. There are limitations, however, in examining the progress and depth of the drought. To this end, monthly and accumulated REIC values were calculated and compared with U.S. Drought Monitor (USDM) drought data. Drought information of the USDM is updated every week (Thursday), and various forms of information are provided, including maps and tables. The map identifies areas of drought and labels them by intensity. D1 (Moderate drought) is the least intense level and D4 (Exceptional drought) the most intense. D0 areas are not in drought, but are experiencing abnormally dry conditions that could turn into drought or are recovering from drought but are not yet back to normal [44]. Monthly REIC is calculated from the first to the last day of each month, and the accumulated REIC is calculated from 1 May to the end of the month. For example, in the case of August, the monthly REIC means the cumulative value from August 1 to August 31, and the accumulated REIC means the cumulative value from May 1 to August 31.

In 2009 and 2010, when relatively higher REIC values were calculated relative to other years, the USDM drought data exhibited a relatively small influence from drought. However, in 2012 and 2017, the monthly and accumulated REIC values were found to be low (Figure 8a,b). The monthly and accumulated REIC values exhibited patterns similar to those of the USDM drought data. Unlike the drought data, however, the REIC values in 2017 were relatively lower than those in 2012. This appears to be because the precipitation and ER were very small in 2017, even though the CU was similar to (or smaller than) that in 2012. In particular, the REIC values of Iowa were very low. The drought data also reported that Iowa reached a peak of 44.6% in August [45].

According to the USDM records, the most severe drought in Illinois occurred on 7 August, 2012, and the drought gradually disappeared (Figure 8c). The Illinois State drought update report [46] revealed that very severe drought was experienced until July 2012, and that the precipitation and temperature of an average year were recovered from August onward. In addition, the drought in some areas was resolved by hurricane Isaac in early September. These local situations were also well-reflected in the monthly and accumulated REIC values (Table 4). In Iowa, although the monthly REIC values in September were higher than the average, the accumulated REIC values had still not recovered. This indicates that agricultural drought was not resolved in Iowa, unlike in Illinois, where the drought was resolved in September (Table 5).

Finally, the spatiotemporal changes in the accumulated REIC values were compared with those in the USDM drought map from July, when the most severe drought was experienced in 2012, to September, when the drought was partially resolved (Figure 9). As a result, the accumulated REIC and the USDM drought map showed similar spatiotemporal changes. In Illinois, a severe drought began from the south regions (southwest and southeast) in early July. In Iowa, a severe drought began from the east regions after mid-July. In both Illinois and Iowa, a severe drought occurred in the entire area on 7 August. In Illinois, the drought began to be resolved from the northeast and east regions after 21 August, and was resolved in most regions (except for the northwest regions) in September. In Iowa, however, the drought was not resolved until September.
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Figure 8. Record of U.S. Drought Monitor (USDM) drought for a specified period.
Figure 9. Comparison of USDM data and accumulated REIC.
| Year | Monthly REIC | Accumulated REIC |
|------|-------------|-----------------|
|      | May | June | July | August | September | May | June | July | August | September |
| 2000 | 0.92 | 0.79 | 0.98 | 0.46 | 0.46 | 0.42 | 0.40 | 0.44 | 0.50 | 0.92 | 0.79 | 0.83 | 0.95 | 0.63 | 0.65 | 0.56 | 0.56 | 0.56 |
| 2001 | 0.97 | 1.00 | 0.27 | 0.32 | 0.33 | 0.35 | 0.48 | 0.46 | 1.82 | 2.07 | 0.97 | 1.00 | 0.44 | 0.41 | 0.38 | 0.37 | 0.41 | 0.40 | 0.46 |
| 2002 | 0.60 | 0.21 | 0.46 | 0.57 | 0.20 | 0.21 | 0.61 | 0.59 | 0.02 | 0.02 | 0.60 | 0.21 | 0.50 | 0.51 | 0.33 | 0.32 | 0.41 | 0.41 | 0.40 |
| 2003 | 0.59 | 0.33 | 0.46 | 0.54 | 0.39 | 0.41 | 0.50 | 0.48 | 1.60 | 1.83 | 0.59 | 0.33 | 0.49 | 0.49 | 0.43 | 0.44 | 0.45 | 0.45 | 0.49 |
| 2004 | 0.96 | 0.90 | 0.32 | 0.38 | 0.44 | 0.46 | 0.74 | 0.71 | 0.01 | 0.01 | 0.96 | 0.90 | 0.48 | 0.47 | 0.46 | 0.46 | 0.54 | 0.54 | 0.52 |
| 2005 | 0.43 | 0.00 | 0.20 | 0.25 | 0.25 | 0.26 | 0.52 | 0.50 | 0.06 | 0.06 | 0.43 | 0.00 | 0.26 | 0.20 | 0.25 | 0.24 | 0.33 | 0.32 | 0.31 |
| 2006 | 0.76 | 0.61 | 0.31 | 0.38 | 0.41 | 0.43 | 0.46 | 0.44 | 0.69 | 0.79 | 0.76 | 0.61 | 0.43 | 0.42 | 0.42 | 0.43 | 0.43 | 0.44 | 0.44 |
| 2007 | 0.63 | 0.69 | 0.53 | 0.66 | 0.33 | 0.34 | 0.48 | 0.45 | 1.01 | 1.16 | 0.63 | 0.69 | 0.56 | 0.67 | 0.43 | 0.46 | 0.44 | 0.45 | 0.45 |
| 2008 | 0.89 | 0.77 | 0.43 | 0.50 | 0.61 | 0.63 | 0.28 | 0.26 | 4.55 | 5.19 | 0.89 | 0.77 | 0.54 | 0.55 | 0.58 | 0.60 | 0.49 | 0.48 | 0.60 |
| 2009 | 0.84 | 0.59 | 0.68 | 0.71 | 0.98 | 0.92 | 0.85 | 0.81 | 1.10 | 1.25 | 0.84 | 0.59 | 0.72 | 0.69 | 0.85 | 0.82 | 0.85 | 0.81 | 0.85 |
| 2010 | 0.79 | 0.49 | 0.91 | 0.97 | 0.75 | 0.76 | 0.48 | 0.46 | 2.46 | 2.81 | 0.79 | 0.49 | 0.87 | 0.87 | 0.80 | 0.80 | 0.71 | 0.69 | 0.77 |
| 2011 | 0.85 | 0.61 | 0.87 | 0.95 | 0.45 | 0.43 | 0.31 | 0.30 | 0.65 | 0.75 | 0.85 | 0.61 | 0.86 | 0.88 | 0.63 | 0.59 | 0.54 | 0.49 | 0.54 |
| 2012 | 0.67 | 0.52 | 0.22 | 0.28 | 0.09 | 0.09 | 0.68 | 0.66 | 6.23 | 7.02 | 0.67 | 0.52 | 0.34 | 0.33 | 0.20 | 0.18 | 0.33 | 0.33 | 0.48 |
| 2013 | 1.00 | 1.00 | 0.74 | 0.89 | 0.49 | 0.46 | 0.31 | 0.30 | 0.22 | 0.25 | 1.00 | 1.00 | 0.81 | 0.91 | 0.63 | 0.62 | 0.54 | 0.51 | 0.52 |
| 2014 | 0.50 | 0.14 | 0.84 | 0.82 | 0.13 | 0.14 | 0.73 | 0.71 | 4.62 | 5.19 | 0.50 | 0.14 | 0.74 | 0.67 | 0.41 | 0.34 | 0.49 | 0.45 | 0.63 |
| 2015 | 0.98 | 0.94 | 0.80 | 0.88 | 0.49 | 0.44 | 0.25 | 0.23 | 1.89 | 2.16 | 0.98 | 0.94 | 0.85 | 0.89 | 0.65 | 0.60 | 0.53 | 0.47 | 0.58 |
| 2016 | 0.89 | 0.78 | 0.09 | 0.11 | 0.69 | 0.67 | 0.46 | 0.45 | 2.37 | 2.71 | 0.89 | 0.78 | 0.27 | 0.24 | 0.48 | 0.49 | 0.48 | 0.47 | 0.54 |
| 2017 | 0.69 | 0.14 | 0.27 | 0.35 | 0.15 | 0.15 | 0.23 | 0.22 | 0.00 | 0.00 | 0.69 | 0.14 | 0.37 | 0.31 | 0.25 | 0.21 | 0.24 | 0.24 | 0.21 |
| 2018 | 0.89 | 0.83 | 0.72 | 0.79 | 0.22 | 0.23 | 0.72 | 0.70 | 3.03 | 3.02 | 0.89 | 0.83 | 0.77 | 0.80 | 0.47 | 0.44 | 0.54 | 0.52 | 0.61 |
| Average | 0.78 | 0.60 | 0.52 | 0.60 | 0.41 | 0.41 | 0.50 | 0.48 | 1.72 | 1.94 | 0.78 | 0.60 | 0.59 | 0.59 | 0.49 | 0.48 | 0.49 | 0.47 | 0.53 |

* C: corn, **B: soybean
Table 5. Results of monthly REIC and accumulated REIC in Iowa, USA.

| Year | May  | June | July | August | September | May  | June | July | August | September |
|------|------|------|------|--------|-----------|------|------|------|--------|-----------|
|      | C    | B    | C    | B      | C         | B    | C    | B    | C      | B         |
| 2000 | 0.93 | 0.91 | 0.67 | 0.82   | 0.39      | 0.39 | 0.32 | 0.31 | 0.05   | 0.05      |
|      |      |      |      |        | 0.02      |      |      |      | 0.07   | 0.05      |
| 2001 | 0.98 | 0.92 | 0.26 | 0.34   | 0.24      | 0.25 | 0.28 | 0.27 | 2.75   | 3.14      |
|      |      |      |      |        | 0.98      |      |      |      | 0.92   | 0.44      |
| 2002 | 0.67 | 0.45 | 0.34 | 0.42   | 0.37      | 0.39 | 0.77 | 0.73 | 0.00   | 0.00      |
|      |      |      |      |        | 0.67      |      |      |      | 0.67   | 0.45      |
| 2003 | 0.36 | 0.02 | 0.68 | 0.85   | 0.40      | 0.39 | 0.08 | 0.07 | 0.10   | 0.11      |
|      |      |      |      |        | 0.37      |      |      |      | 0.36   | 0.02      |
| 2004 | 0.35 | 0.86 | 0.74 | 0.50   | 0.49      | 0.50 | 0.09 | 0.59 | 0.11   | 0.76      |
|      |      |      |      |        | 0.35      |      |      |      | 0.86   | 0.63      |
| 2005 | 0.58 | 0.26 | 0.62 | 0.74   | 0.25      | 0.26 | 0.52 | 0.50 | 1.03   | 1.18      |
|      |      |      |      |        | 0.57      |      |      |      | 0.61   | 0.65      |
| 2006 | 0.53 | 0.41 | 0.64 | 0.32   | 0.26      | 0.21 | 0.62 | 0.54 | 1.58   | 2.51      |
|      |      |      |      |        | 0.62      |      |      |      | 0.53   | 0.41      |
| 2007 | 0.92 | 0.89 | 0.44 | 0.54   | 0.31      | 0.32 | 1.45 | 1.37 | 1.55   | 1.74      |
|      |      |      |      |        | 0.92      |      |      |      | 0.92   | 0.89      |
| 2008 | 0.96 | 0.86 | 0.51 | 0.63   | 0.60      | 0.62 | 0.22 | 0.21 | 2.17   | 2.48      |
|      |      |      |      |        | 0.96      |      |      |      | 0.96   | 0.86      |
| 2009 | 0.77 | 0.48 | 0.61 | 0.66   | 0.41      | 0.42 | 0.59 | 0.56 | 0.00   | 0.00      |
|      |      |      |      |        | 0.77      |      |      |      | 0.48   | 0.66      |
| 2010 | 0.56 | 0.27 | 1.21 | 0.80   | 0.87      | 0.89 | 0.96 | 0.91 | 1.29   | 1.48      |
|      |      |      |      |        | 0.56      |      |      |      | 0.56   | 1.01      |
| 2011 | 0.91 | 0.71 | 0.80 | 0.84   | 0.25      | 0.26 | 0.42 | 0.40 | 0.74   | 0.84      |
|      |      |      |      |        | 0.74      |      |      |      | 0.41   | 0.71      |
| 2012 | 0.59 | 0.70 | 0.37 | 0.48   | 0.05      | 0.05 | 0.38 | 0.37 | 1.07   | 1.23      |
|      |      |      |      |        | 0.59      |      |      |      | 0.59   | 0.70      |
| 2013 | 0.95 | 0.85 | 0.66 | 0.76   | 0.14      | 0.15 | 0.27 | 0.26 | 0.29   | 0.33      |
|      |      |      |      |        | 0.95      |      |      |      | 0.95   | 0.85      |
| 2014 | 0.37 | 0.05 | 0.63 | 0.71   | 0.27      | 0.27 | 0.70 | 0.66 | 1.65   | 1.86      |
|      |      |      |      |        | 0.63      |      |      |      | 0.37   | 0.05      |
| 2015 | 0.86 | 0.66 | 0.56 | 0.69   | 0.29      | 0.30 | 0.42 | 0.40 | 0.69   | 0.79      |
|      |      |      |      |        | 0.86      |      |      |      | 0.66   | 0.66      |
| 2016 | 0.95 | 0.88 | 0.08 | 0.11   | 0.41      | 0.42 | 0.35 | 0.34 | 1.57   | 1.80      |
|      |      |      |      |        | 0.95      |      |      |      | 0.88   | 0.29      |
| 2017 | 0.65 | 0.00 | 0.19 | 0.24   | 0.10      | 0.10 | 0.50 | 0.48 | 0.00   | 0.00      |
|      |      |      |      |        | 0.65      |      |      |      | 0.00   | 0.00      |
| 2018 | 0.42 | 0.34 | 0.61 | 0.76   | 0.09      | 0.10 | 0.66 | 0.63 | 0.33   | 0.38      |
|      |      |      |      |        | 0.33      |      |      |      | 0.42   | 0.34      |
| Average | 0.70 | 0.55 | 0.56 | 0.60   | 0.33      | 0.33 | 0.51 | 0.51 | 0.89   | 1.09      |
|      |      |      |      |        | 0.70      |      |      |      | 0.55   | 0.60      |
4. Conclusions

In this study, a cell-based daily soil water analysis model (CellSW) was developed and used to continuously analyze soil moistures to analyze water balance items, such as the effective rainfall (ER), consumptive use (CU), irrigation requirement (IR), and water deficit (WD). In addition, an agricultural drought index was presented for defining the tendency or depth of drought using the soil water balance, and its spatiotemporal characteristics were compared with local drought data.

1. The developed CellSW could estimate the soil moisture without spatiotemporal limitations by reflecting differences by period depending on the soil properties, crop types, and crop growth stages.

2. The water balance results, including the CU, ER, IR, and WD, were analyzed. The CU was defined as the crop evapotranspiration. If photosynthesis by evapotranspiration is active, a high yield can be expected, but it can be a burden in terms of the water balance, owing to the increase in the IR. The ER is the amount of precipitation contributing to the actual soil moisture. A large ER is favorable in terms of water balance, as it fills the CU and reduces the IR. The WD is the water quantity that does not satisfy the CU. As it increases, the water balance becomes worse. In the last 19 years (2000–2018), the water balance was found to be in excellent condition in 2009 and 2010. In contrast, the CU, ER, and IR were all in poor condition in 2005, 2006, 2012, and 2017. In particular, both soybeans and corn were in poor condition in 2012, indicating extreme drought stress.

3. An agricultural drought index was calculated using the soil water balance results, and was defined as a lack of soil moisture. The rainfall effectiveness index for crop (REIC) was defined as the ratio of the ER to the CU. Higher REIC values indicated favorable water balance conditions, and low sensitivity to agricultural drought, and vice versa. The REIC values were very low in 2005 and 2017 in Illinois and in 2012 and 2017 in Iowa, when the CU was relatively large and the ER was relatively small. The REIC was found to have fluctuations over time and regional differences, but was not significantly different between crops (corn and soybeans).

4. To examine the progress and depth of drought, monthly and accumulated REIC values were calculated and compared with the USDM drought data and map. It appears that the use of water was significantly difficult in terms of crop cultivation in 2012 and 2017. The REIC, however, showed that water balance was in a poorer condition in 2017 than in 2012. This appears to be because the REIC was affected by the very small ER in 2017. Although the CU was similar or slightly smaller than that in 2012, the precipitation was only 35–57%, and the ER was only 42–49% of the average values over the last 19 years (2000–2018). When the drought situations in 2012 were compared, the spatiotemporal changes in the accumulated REIC were similar to those in the USDM drought map.

In agriculture, soil moisture is a major means for managing agricultural productivity [47]. Drought assessments and index calculations using soil moisture have been performed to establish irrigation scheduling or to identify the growth conditions of crops [48]. The observation of soil moisture, however, is very difficult, owing to regional limitations and large spatiotemporal fluctuations. Therefore, in areas where direct measurement is difficult or the available data are limited, a model that traces changes in soil moisture based on the water balance in agricultural lands can be effective. In this study, it was possible to analyze various crops, soils, and weather conditions through a GIS-based soil water balance model, regardless of the spatiotemporal resolution. It is expected to be highly useful for analyzing the water balance of field crops and drought monitoring.
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