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Review

Energy Compensation for Crop Growth under Plastic Mulching: Theories, Models, and Limitations

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Abstract: Plastic film mulching (PM) is a useful agronomic means to adapt to the environmental conditions of dryland agriculture and improve crop production. To improve the theoretical framework of PM technology, this study focuses on the interaction between the soil temperature change caused by PM and crop growth. The definition, action mechanism, and simulation of the compensatory effect of PM on growing degree days are introduced to reveal the effect of soil temperature under PM on crop development and growth. Our summary shows that the strength of the warming effect changes with the growth and development of crops, strengthening during the early stage of crop growth and gradually weakening as a crop canopy develops. Generally, the warming effect has a good promotion effect on crop growth, but the crop growth is hampered even with a yield reduction when the increased soil temperature caused by PM exceeds the tolerant temperature for plant growth. Moreover, the compensatory effect of PM could be used to quantify the growth and development of crops under PM and has been widely applied to cotton, corn, winter wheat, and rice. The compensation coefficient is larger in the early stage of crop growth than in the later stage. The compensation coefficient has certain differences for the same crop because of the influence of climate factors, soil moisture content, and soil microtopography. In future research, the theoretical integration of the safety period of PM and the time threshold of the compensatory effect could be theoretically interpreted, and the construction of the compensatory effect module in the crop models will also be an important issue.

Keywords: plastic film mulching; crop model; time threshold; dryland; growing degree day

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1. Introduction

Since 1990, crop yields have stagnated in many parts of the world [1]. In recent years, the COVID-19 pandemic has spread globally and posed a grave threat to human life and property. Coupled with geopolitical and administrative uncertainties, a global food crisis has developed and intensified dramatically. As such, innovative solutions are needed to increase the resource use efficiency of cropping systems to produce more grains per unit area. In the past 60 years, most increases in the world's food supply have resulted from increasing crop yield as cropland areas have remained nearly constant; while additional lands remain that can be brought into production, they tend to be less productive and more environmentally sensitive than land currently in agricultural production [2]. In terms of the future potential of global food production, moist areas with good environmental conditions have already realized a great deal of production potential based on highly intensive land use, intensive cultivation, and multi-cropping. Unless a breakthrough in biotechnology is achieved, the potential for significant increases in food production is limited in these regions [3]. Therefore, dryland agriculture (DA) must play an increasingly important role in addressing and overcoming the global food crisis [4].

Global drylands encompassing arid, semiarid, and dry sub-humid areas cover about 41% of the Earth's terrestrial surface and are home to more than one-third of the world's population [5]. Dryland areas are one of the most sensitive areas to climate change and human activities because of the infertile soil and sparse vegetation [6,7]. DA is commonly constrained by low temperature, drought, and inner-annual variation in precipitation [8–10]. Since water is the primary limiting factor for DA, many measures are carried out to conserve water, of which mulching measures (e.g., straw mulching and plastic film mulching) are the most commonly used. Many experiments have indicated that the technology of plastic film mulching (PM) can partly address and resolve the issues faced by producers in dryland areas [11–15] as it could effectively increase soil temperature, conserve and save soil moisture, and provide a relatively suitable and stable growing environment for crops [16–18], and it has been widely used across the world [19–21]. The effects of PM on crop productivity mainly include four aspects. First, PM practices can create a physical barrier on the soil surface, thereby reducing soil evaporation and improving soil hydrothermal conditions. Accordingly, PM can promote crop leaf transpiration and effectively improve crop water use efficiency [22,23]. Second, PM practices can enhance root nutrient uptake by accelerating the mineralization of soil organic nitrogen [24,25] and promote root growth by improving soil hydrothermal conditions [26]. Third, ridge-furrow mulching systems can increase soil water infiltration by collecting rainfall [27] and reduce soil nutrient leaching [28]. In addition, PM practices can inhibit weed development in conjunction with other field practices [29]. All the aforementioned effects may improve crop productivity in dryland regions.

Temperature is one of the main environmental factors that affect crop growth and development, and every 1 K change in soil temperature has a great impact on crop growth and development [30]. Crop plants develop faster when temperatures are warmer and more slowly when temperatures are cooler. Since the 1730s when Reaumur introduced the concept of heat units (or thermal time), many methods of calculating heat units have been used successfully in the agricultural sciences [31]. Commonly used terms for thermal time are growing degree days (GDDs), growing degree units, or heat units, and different methods exist for calculating heat units depending on the crop or biological organism [32], classifying crop species, hybrids, and varieties [33], or evaluating climate for specific crop-management combinations [34–36].

According to the concept of accumulated GDDs, crops require a certain amount of GDDs depending on the cumulative air temperature to reach a certain phenological stage [37]. The field experiment shows that the amount of GDDs should be the sum of the cumulative temperature obtained by the aboveground and underground parts of plants [38]. Thus, the GDD estimate is most accurate when GDDs are calculated using soil temperatures rather than air temperatures early in the growing seasons [39]. Many studies have proved that PM could help increase the soil temperature by reducing heat loss from the soil through long-wave radiation at night (termed as the warming effect under PM) [40–42], due to which plants under PM would reach the same phenological stage at an earlier thermal time than plants under non-mulching (NM) practices [43]. However, how the increased soil temperature influences crop development is still unclear. Conventional crop models rarely account for the warming effect of PM measures on crop development [44–46]. No comprehensive studies have evaluated the interaction between soil temperature and the crop growth and development under PM practices.

To comprehensively analyze the influence of PM practices on soil temperature and crop growth and development, and to more efficiently use PM techniques in drylands, this study is based on a review of the relevant literature. Generally, the plastic film in this study is the common agricultural mulching film mostly made of polyethylene. It usually includes transparent and black colors and most of them have a 0.008–0.01 mm thickness. The aims of this study were to (1) investigate the effects of PM on soil temperature and analyze the underlying processes and factors, (2) reveal the effect of soil temperature under PM on crop development and growth, (3) quantify the energy transfer under PM practices, (4) introduce the definition, action mechanism, and simulation of the compensatory effect of PM on growing degree days, and (5) provide insights for limitations, model development, and future research needs on PM. This study could enrich the theoretical system and construct the theoretical framework of PM technology, provide guidelines for optimizing PM measures, extend crop models, and contribute to dryland agricultural productivity.

2. Effects of PM on Soil Temperature

2.1. Mechanism of the Warming Effect under PM

As one layer of physical barrier, PM can influence soil surface temperature in the following ways: (1) PM can hinder heat exchange near the soil surface and inhibit latent heat loss caused by evaporation; (2) the long-wave solar radiation during daytime cannot pass through the mulching film and may be reflected into the air near the ground, which is converted into heat energy and raises the air temperature near the soil surface; (3) short-wave radiation can penetrate through the cover film layer to the ground, by which some is converted into heat energy, resulting in temperature increases; and (4) PM at night can inhibit long-wave radiation from the ground, reducing soil heat loss, and partially promote heat transfer to the deep soil via heat conduction [47–50]. The above cumulative effects increase the net radiant heat income and effectively increase the soil temperature. While degradable plastic film has a similar warming effect to conventional plastic film [51,52], it will weaken gradually until it vanishes as the mulching film degrades with time [53].

Accordingly, many factors can affect the warming effect of PM, such as local climatic conditions, mulching methods, soil depths, film types, and crop types [11,54–58]. Local climate conditions are one of the most important factors that determine soil temperature variation. Studies have demonstrated that the warming effect of PM varies with weather conditions, indicating that PM increases soil temperature well on sunny days and unsatisfactorily on rainy days [59]. The warming effect is also variable due to diurnal temperature variation. Compared with the bare field, PM can increase the soil temperature by 2–10 K during the day but only by 2–4 K at night [60]. Zhang et al. [61] reported that the warming effect of PM is more obvious in a cold environment than in warm regions. Zhang et al. [15] suggested that PM covering in a field in a high-altitude region (e.g., Gansu Province) could increase soil temperature more significantly than in a low-altitude region (e.g., Shandong Province) under the same mulching method in China. The warming effect of PM could also be affected by application methods. While both methods of flat mulching and ridge-furrow mulching could increase soil temperature, the warming effect under the flat-mulching treatment is more significant than that under the ridge-furrow mulching treatment, and the warming effect under whole coverage (i.e., covering the whole soil surface with PM) is better than that under half coverage [54–63]. The soil temperature is usually measured within a 20 cm depth of topsoil. The influence of PM on soil temperature [54] and the diurnal variation amplitude of soil temperature gradually weaken with the increase in soil depth [55]. With regard to colors of plastic film, previous studies confirmed that transparent film has a better warming effect than black film for both conventional and degradable film [53,56,57].

The warming effect of PM can also change with the growth and development of crops. During spring maize-growing seasons, the warming effect of PM on the soil temperature is mainly active from the seedling stage to the jointing stage and will fade after jointing [58,64,65]. In summer maize-growing seasons, however, the warming effect of PM in July is much stronger than that in August and September [66]. PM has the most significant warming effect on spring wheat beginning from 15 days after sowing [67]. However, the warming effect during winter wheat-growing seasons gradually diminishes after the jointing stage [68].

The decreased warming effect of PM at later crop growth stages could be attributed to the following reasons. First, the crop canopy grows rapidly with plant height and aboveground biomass increases in later growth stages, resulting in dense leaves effectively blocking direct sunlight and shading the ground surface, thereby reducing the heat acquisition at the soil surface [58,68]. Second, the warming effect of PM is related to the topsoil water content. PM can more effectively retain soil moisture compared with the NM practice due to reduced surface evaporation. The increased soil moisture leads to greater soil specific heat, which means that the 1 °C increase in surface soil under the PM condition requires more heat energy than that under the NM treatment. The soil surface temperature rises slowly under PM and is similar to or lower than that under NM because of the increased soil water content and the soil specific heat. For instance, due to the aforementioned reasons, soil temperature under PM increases much more slowly than that under NM after regreening during the winter wheat-growing seasons. The soil temperature under PM shows a reduction trend unlike that under NM [69]. Therefore, the warming effect of PM is usually present in the early stages of crop growth and then gradually weakens after crop canopy closure [70,71].

2.2. Warming Effect of PM on Crop Development and Growth

The warming effect of PM usually promotes crop growth. Previous studies showed that for overwintering and early spring crops, PM is conducive to avoiding the negative effects of cold damage on seed germination and seedling morphogenesis in spring and autumn, which strengthens crop seedling development by promoting seed germination and root growth [72–75]. The warming effect of PM can effectively mitigate the low-temperature stress in cold regions, expand the planting areas of crop varieties, and maintain grain yield [76]. Therefore, the warming effect of PM could move the critical latitude of suitable crop planting areas northward by increasing the GDDs during crop-growing seasons [77]. For example, the warming effect is of great significance for extending the cultivation of medium–late ripe, high-yield, and high-quality varieties to some high-latitude regions and high-altitude mountainous areas in northern China with insufficient accumulated GDDs and a limited frost-free period [41].

However, the increase in soil temperature caused by PM is not always beneficial to crop growth [78]. Studies have shown that the lower limit of temperature for maize growth is 6–9 °C [79], and the optimal temperature is 25–35 °C [80]. The optimum temperature for cotton growth is around 30 °C, with the maximum temperature not exceeding 35 °C [81]. For the initial development stage of maize plant leaves, the minimum, optimum, and maximum temperatures were 7.3 ± 3.0 °C, 31.1 ± 1.7 °C, and 41.3 ± 1.9 °C, respectively, during the maize-growing seasons and 10.7 ± 0.6 °C, 29.5 ± 0.8 °C, and 42.5 ± 12.5 °C, respectively, during the rice-growing seasons [82]. When the soil temperature is excessively high caused by PM, crop growth is limited, and even production is reduced. Studies have demonstrated that PM can induce high near-surface temperatures, which may cause the premature senescence of maize plants at the grain filling stage and shorten the duration from the grain filling stage to the maturity stage [83]. Continuously high soil temperature can cause poor soil aeration, resulting in the substantial drying of roots and a decline in root activity during the growth period of maize, which can lead to an insufficient nutrient supply during the later growth period of maize and inhibit plant growth with yield reductions [84,85]. In the key growth period of potato, high-temperature stress caused by PM significantly restricts tuber formation [86]. In addition, the warming effect can encourage a rapid growth of crop shoot and root in the early growing stages with a high consumption of soil moisture. Hence, insufficient precipitation in the later growing stage can easily decrease soil moisture, resulting in a lower crop yield [87,88]. To alleviate and eliminate the adverse impacts of the PM warming effect on crops, removing film in the appropriate time has been the primary solution [89,90].

3. Soil Energy Transfer under PM

With the wide application of PM measures, evaluating the long-term effects of PM measures on soil physical–chemical properties and the environment is critical. Compared with long-term field experiments, crop growth models can not only save time, labor, and material resources but also expand the spatial and temporal distribution of experimental treatments [34]. Therefore, the development and application of a crop model are among the most important ways to evaluate PM effects. To simulate crop growth and soil water balance under PM measures, the first step is to improve the module for the energy transfer process under PM conditions in associated crop growth models.

Liakatas et al. [91] studied the effect of continuous film mulches on soil temperature and the flow of heat in the soil and analyzed the sensible and latent heat exchange between the soil surface and the air in contact with it. The supply of radiant energy at the soil surface is usually expressed as a net radiative energy flux (R_n) given by the following relation:

$$R_n = (1-\rho)S + \epsilon L_d - L_u \quad (1)$$

where S is the flux density of solar radiation on a horizontal surface, ρ is the surface reflectivity for a certain waveband (approximately 0.3–3 µm), and ϵL_d and L_u are the absorbed and emitted fluxes of thermal radiation, respectively, with all fluxes being expressed in W m^{-2}.

Chung and Horton [92] constructed a two-dimensional soil moisture and heat conduction model under partial mulching by using the alternating direction implicit finite difference method. The energy balance formula for the NM and the mulching surfaces, as well as the mulching and soil interface, is as follows:

$$R_n - H_s - LE - G = 0 \quad (2)$$

$$R_n - H_s - M_s = 0 \quad (3)$$

$$M_s - LE - G = 0 \quad (4)$$

where R_n is the net radiation (W m^{-2}); H_s is the air sensible heat flux (W m^{-2}); M_s is the sensible heat flux of plastic film (W m^{-2}); L is the latent heat of vaporization (J m^{-3}); E is the evaporation flux (m s^{-1}); and G is the soil heat flux (W m^{-2}). The above formula parameters take upward transmission as the positive direction. In earlier studies, researchers mainly focused on the energy balance of microclimates under PM, and little consideration was given to the effects of PM on crop growth and development.

To accurately estimate crop evapotranspiration (ET) under PM, Li et al. [93] introduced the covering rate of PM (the ratio of the covered area to the total area) into the original Shuttleworth–Wallace model and simulated soil water–heat transfer processes and maize ET under PM, where the plant canopy development was fully considered by using the canopy resistance coefficient. The energy flux from the soil–mulch–canopy system is given by

$$\begin{aligned} \lambda ET &= \lambda T + (1-f_m)\lambda E_s + f_m \lambda E_m \\ &= C_c PM_C + (1-f_m) C_s PM_S + f_m \lambda E_m \end{aligned} \quad (5)$$

where λET is the latent heat flux (W m^{-2}); λT is the latent heat flux (W m^{-2}) caused by crop transpiration; f_m is the plastic film coverage; λE_s is the latent heat flux (W m^{-2}) caused by soil evaporation; λE_m is the latent heat flux (W m^{-2}) caused by the evaporation of the coated soil; C_c is the canopy resistance coefficient; PM_C is the function of crop transpiration (W m^{-2}); C_s is the coefficient for soil surface resistance; and PM_S is the function of soil evaporation (W m^{-2}). The modified Shuttleworth–Wallace model performed well in simulating maize ET especially after the canopy fully covered the ground surface [93].

Given the PM coverage and duration, Han et al. [44] added a plastic film module to the original module of soil and air in DNDC according to the transfer law of heat in different media of atmosphere, plants, plastic film, and soil; separated the air layer from the soil layer; and then added the film mulching module in the DNDC model [44]. The new soil surface temperature is determined by the difference between the air and soil temperatures as well as by the thickness and thermal conductivity of the film

$$dH = (T_{soil} - T_{air}) \times D_{film} \times TC_{film} \times dt \tag{6}$$

$$T_{soil(\mathrm{i+1})} = T_{soil(\mathrm{i})} + dH/SH_{soil} \tag{7}$$

where dH is the heat flux (J s^{-1}) from soil to air through plastic film; T_{soil} and $T_{soil(\mathrm{i+1})}$ is the soil temperature in different layers (°C); T_{air} is the air temperature (°C); D_{film} is the film thickness (m); TC_{film} is the thermal conductivity of plastic film (0.25 J s^{-1} m^{-1} K^{-1}); dt is the time (s); and SH_{soil} is the specific heat of soil (J kg^{-1} K^{-1}). In recent years, the rice mulch dry production system has developed rapidly. Previous authors solved the problem of the mulch warming effect simulated in CERES-Rice and WHCNS models by using Equations (6) and (7) [44,94,95].

On the basis of Formula (1), the RZ-SHAW model refines the classification of solar radiation [96], which is calculated as follows:

$$R_n = S_b + S_d - S_u + L_d - L_u \tag{8}$$

where R_n is the total solar radiation (W m^{-2}); S_b is the downward short-wave radiation (W m^{-2}) from the medium surface; S_d is the downward diffusive radiation (W m^{-2}) on the surface of the medium; S_u is the short-wave radiation (W m^{-2}) reflected from the medium surface to the air; L_d is the long-wave radiation emitted downward from the atmosphere (W m^{-2}); and L_u is the long-wave radiation (W m^{-2}) reflected from the surface of the medium to the air. On the basis of the absorption and reflection rules of short-wave and long-wave solar radiation at the mulch–air interface and the mulch–soil interface, the RZ-SHAW model takes into account and revises the effects of film mulching measures on soil temperature, water vapor transformation, and energy transfer processes [96]. A comparative study found that the RZ-SHAW model outperformed the improved DNDC model when it came to simulating the change in soil surface temperature [97].

From evaluating the soil energy balance with mulching to simulating soil evaporation and temperature under PM, cultivating an understanding of the internal microcosmic and dynamic detailed variation in energy transport processes is the main developing trend of studies on specific characteristics. Under NM conditions, because soil temperature is closely related to air temperature, the relationship between heat energy and the crop growth process can be accurately quantified by the accumulated effective air temperature, i.e., GDDs [98]. However, the process of soil heat transfer is significantly modified by PM, and the warming effect has significantly weakened the dependence of soil temperature on air temperature. The advanced crop growth and development, i.e., the acceleration of crop-growing stages caused by PM, cannot be well explained from the perspective of accumulated GDDs based on air temperature. Most studies on the warming effect of PM in crop models mainly focus on the influence of PM on the energy transport processes, which lie in soil physics. The warming effect of PM on crop development belongs to the category of bioecology and is termed the compensatory effect under PM.

4. Compensatory Effect under PM

4.1. Definition

Studies have found that the increased soil temperature by PM has a good compensatory effect on the growing degree days based on the air temperature (GDD$_\mathrm{a}$), allowing crop growth and development to be regulated effectively [99,100]. That is, a thermal time lag of plant development occurs between NM and PM, and the increased soil temperature under PM compensates for the thermal time lag [43,69]. This phenomenon is known as the compensatory effect of PM [101], which can objectively reflect the influence of PM on crop growth and development (Figure 1).

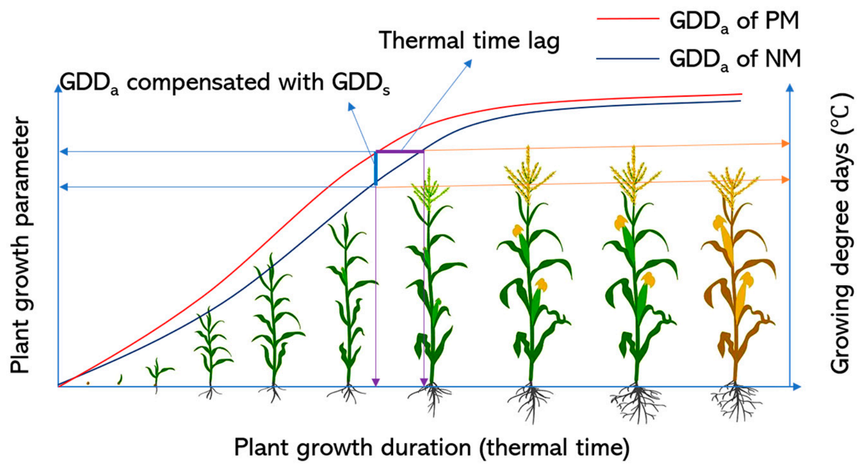


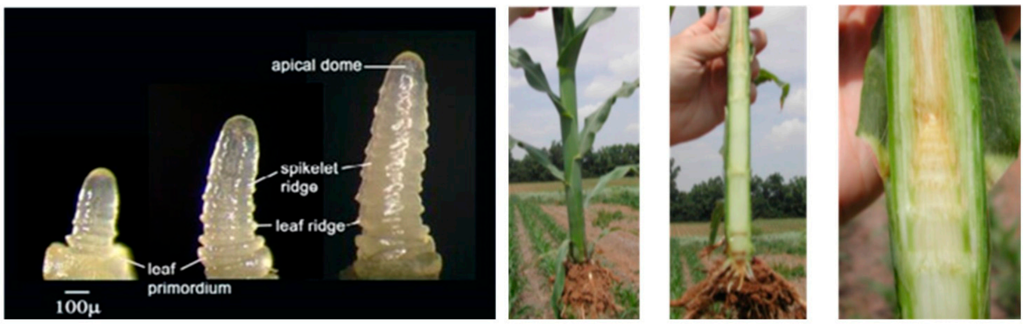
Figure 1. Schematic diagram for the compensatory effect of plastic film mulching. The plant growth parameter could be plant height, leaf number, or aboveground biomass; GDD_a: growing degree days based on the air temperature; GDD_s: growing degree days based on the soil temperature.

The compensatory effect of PM has been applied to quantify cotton growth development in early years (the Cotton Science Group of China Film Mulching Cultivation Research Association, 1988; [81,102–104]). With the popularization and application of PM technology, researchers have also found the compensatory effect of PM in growing seasons of wheat, maize, and rice [94,95,105,106]. Quantifying this effect has good application value for the quantitative description of the crop growth and development process under PM conditions, the improvement of crop models, and further evaluation and optimization of film mulching measures.

4.2. Terminal Time of Compensatory Effect under PM

The direct manifestation of the PM compensatory effect is the acceleration of crop growth and development. Previous studies on the compensatory effect of PM mainly focused on crop growth during relatively warm seasons, e.g., cotton- and maize-growing seasons [81,107], where PM practices would increase topsoil temperatures throughout the crop-growing season. Naturally, these studies imply that the compensatory effects of PM synchronize and continue throughout the crop-growing seasons [43,100,108]. However, PM increases soil temperature only within a limited period during the winter wheat-growing season, and the compensatory effect is effective only when the soil temperature is increased [43,109]. In the summer maize-growing seasons, unfavorably delayed senescence occurs under PM due to the improved soil hydrothermal conditions [43,109,110], which is inconsistent with the continuity of the compensatory effect on plant development. Moreover, with the development of a crop canopy, solar radiation cannot directly reach the ground when leaves shade rows, resulting in the compensatory effect weakening gradually or even disappearing [15,57]. Thus, a time threshold (i.e., a terminal time) may exist for the compensatory effect of PM depending on when the apical meristem emerges from soil or the soil temperature stops increasing (Figure 2).

Furthermore, the compensatory effect of PM is closely linked to plant development. The primordium initiation depends on the temperature of the apical meristem [111,112], which remains underground until stem extension begins [113,114]. Thus, the increased soil temperature would significantly influence apical meristem development and dominate the crop plant growth before stem extension [115,116]. With the development of the plant, the influence of soil temperature on the apical meristem development gradually weakens after the stem has elongated and emerged from the soil, and then the air temperature around the crop canopy gradually becomes the dominant factor for plant development [117].



a. The initiation of leaf primordium (Taking wheat as an example)

b. The apical meristem emerges from soil (Taking maize as an example)

Figure 2. Initiation of leaf primordium and the emergency of apical meristem from soil, taking wheat (**a**) and maize (**b**) as example, respectively.

Previous studies found that stem extension starts around the period of terminal spikelet, when the leaf number is between 7 and 12 during the wheat-growing seasons [118]. For maize, meristem emergence from the soil surface occurs when the plant has six fully expanded leaves or 10 leaf tips [116,119,120]. From the above growth periods, the plant apical meristem that emerges from the soil is roughly between the regreening and jointing stage in the wheat-growing season and between the 5-leaf and 10-leaf stage during the maize-growing season. The transition of the dominant factor between topsoil temperature and air temperature objectively reflects the rationality of the terminal time for the PM compensatory effect.

4.3. Determination of the Terminal Time

When the theoretical framework for the terminal time for the PM compensatory effect is completed, the next task is to determine value ranges of the terminal time. The remarkable observation for the PM compensatory effect is the acceleration in plant development [81,107]. Given the theoretical framework based on the apical meristem development, the indices that coincide with the apical meristem development should be measured first. Plant growth and development are continuous and have no obvious singularity in one treatment. Thus, researchers have to search for the distinction between NM and PM treatments in field experiments for the terminal time. In the field experiment, growth and development indices under different treatments, e.g., PM and NM treatments, are usually measured. In fact, many studies have observed similar phenomena with the compensatory effect under PM. For instance, a certain period of the "Haun stage" has a faster leaf appearance rate and shorter phyllochron than later wheat-growing periods [111,112]. Moreover, numerous crop growth processes, such as the development of shoot height, leaf area index, aboveground biomass, and root length density, coincide approximately synchronously with the apical meristem development and the leaf occurrence process. Accordingly, crop growth and development indicators may be used to identify differences between NM and PM treatments and determine the terminal time for the PM compensatory effect in plant development (Figure 3).

In the field experiment, crop growth and development indicators are usually measured in some time interval. The time discontinuity may cause the absence of key points in crop growth and development. To better differentiate crop growth indicators between PM and NM, the simulation of crop dynamics provides the possibility to explicitly explore the PM compensatory effect under different mulching treatments. A simple and accurate model of the cumulative growth index could provide a usual description of the crop growth process. Many simplified mathematical models have been used to simulate plant growth or organ biomass accumulation, such as the logistic model [121–125]. Among these models, the logistic model is the most frequently used in dynamic crop growth simulation [126].

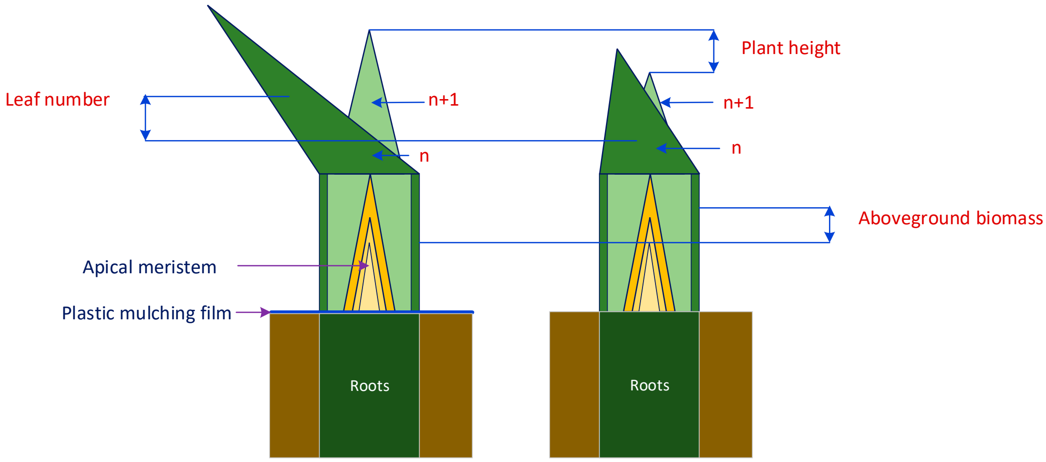


Figure 3. Crop growth and development indicators for the PM compensatory effect.

These crop growth processes usually resemble a sigmoidal-shaped response curve that relates the cumulative quantity to time (e.g., days) or cumulative thermal energy, e.g., GDDs. These response curves typically display an initial lag period, followed by an exponential period of rapid accumulation, and then the curve levels to a plateau when one process is nearly complete [127,128]. The logistic equation includes a sigmoid function to allow for smooth transitions between growth phases. Importantly, the characteristic parameters of the curve, such as the inflection points and the maximum slope, have a biological meaning in terms of the rapid crop growth stage among growth phases and growth rate by mathematical derivation [54,129].

Ding et al. [43] showed that the logistic equation with thermal time sufficiently characterized the cumulative processes of plant height and aboveground biomass in a PM treatment (Figure 4). The logistic curve equation can better fit the cumulative process of different crop growth indicators, and the changes in the curve, such as the different positions of inflection points on the curve, can better characterize and quantify the process of crop growth and development. The logistic equation takes the second derivative of Y and sets the equation equal to zero. Then, the maximum relative growth rate (or maximum cumulative rate; v_m) and the corresponding occurrence time (t_m) can be solved on the S curve. The logistic equation takes the third-order derivative of Y and sets its equation equal to zero. Values of the two inflection points t_1 and t_2 on the S curve can be obtained. All of the above parameters are the eigenvalues on the S curve of the logistic equation. These eigenvalues are calculated as follows:

$$t_1 = \frac{1}{b}\ln\left(\frac{2+\sqrt{3}}{a}\right) \tag{9}$$

$$t_2 = \frac{1}{b}\ln\left(\frac{2-\sqrt{3}}{a}\right) \tag{10}$$

$$v_m = -\frac{bk}{4} \tag{11}$$

$$t_m = -\frac{lna}{b} \tag{12}$$

$$t_d = t_2 - t_1 \tag{13}$$

where t_1 and t_2 are the first and second inflection points (°C d) of the logistic equation, respectively, and the time period between t_1 and t_2 is the rapid growth or accumulation stage of crops, which can be defined as the rapid growth period of crops. Therefore, t_1 and t_2 are the start and end time of the rapid growth period of crops, respectively. The terms v_m and t_m are the maximum growth rate and the occurrence time of the maximum growth rate, respectively. In the process of simulating plant height and shoot biomass, the unit of v_m is mm °C^{-1} d^{-1} and kg ha^{-1} °C^{-1} d^{-1}, and the unit of t_m is °C d. t_d is the duration of the rapid growth phase (°C d).

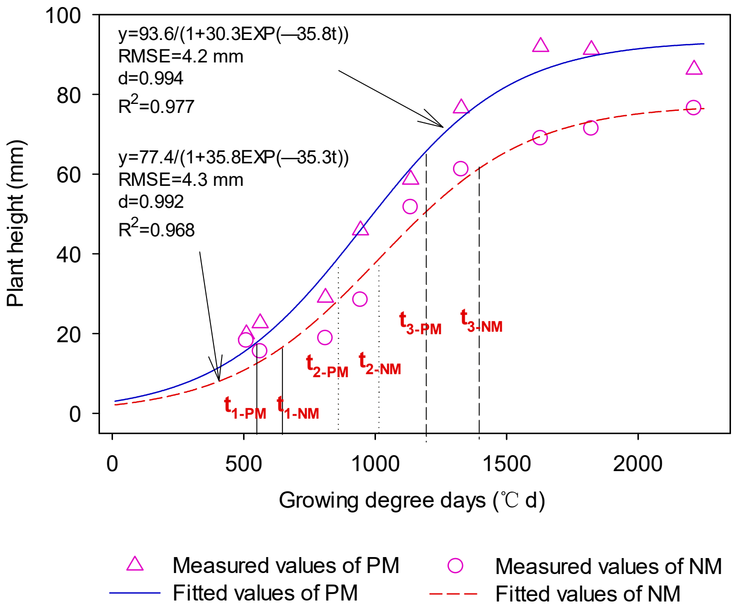


Figure 4. Comparison of crop plant height accumulation processes under PM and NM during the winter wheat-growing season.

The logistic equation could well simulate the accumulation process of plant height (Figure 4). When the plant height is at the same level, the PM treatment requires less thermal time than the NM treatment. That is, the PM treatment reaches the same level of plant height earlier than the NM treatment. Moreover, the eigenvalues of the logistic equation perform well and precisely reflect the difference in the accumulated thermal time with plant development both in PM and NM treatments. On the basis of the above advantages of the logistic equation, Ding et al. [43] quantitatively assessed the response of biomass and plant height in the winter wheat–summer maize rotation system to the compensatory effect of PM. In ref. [69], the logistic equation performs well in representing and quantifying the compensatory effect of PM; the compensatory effect under PM during winter wheat-growing seasons disappears because PM stops increasing the soil temperature around the regreening stage, and the thermal time node t_2 for plant height on the logistic curve can be used to estimate the terminal time for the compensatory effect window under PM for winter wheat. For summer maize, the compensatory effect under PM reaches a plateau through unfavorably delayed senescence due to the modified soil hydrothermal conditions under PM. Thermal time node t_3 for plant height on the logistic curve can be used to estimate the terminal time in summer maize-growing seasons.

4.4. Calculation and Application of the Compensatory Coefficient

The compensatory coefficient in the compensatory effect of PM was first proposed by the Cotton Science Group of China Film mulching Cultivation Research Association (1988) and is mainly used to quantify how much a soil temperature increase compensates for GDD_a when cotton is covered with PM. To calculate the number of days required for the crop growth stage, the first calculation formula of the compensatory coefficient is as follows:

$$n = \frac{A}{t + \frac{P}{k}C_c} \quad (14)$$

where n is the number of days required by a certain growth stage of the mulched crop (d); A is the GDD_a required by the non-mulched crop at the growth stage (°C d); t is the average value of daily effective air temperature at the growth stage (°C); P is the soil temperature increment value under PM (°C); k is the ratio of the daily effective soil temperature (i.e., GDD based on the soil temperature; GDD_s) and the daily effective air temperature (i.e., GDD_a) under PM; and C_c is the compensatory coefficient. The above equation shows that when A is basically constant, the compensatory effect of PM is positively correlated with k and negatively correlated with t. In Equation (14), C_c is defined as the ratio of the effective air temperature increment caused by the warming effect under PM and the initial effective air temperature. The calculation of $\frac{P}{k}$ transfers the GDD_s increment to the GDD_a increment.

For ease of use, researchers define the compensatory coefficient and directly build the relationship between the effective soil temperature increment and the initial GDD_a. In this condition, the compensatory coefficient is defined as the amount of GDD_a compensated by every 1 K increment in the GDD_s under PM [47,104]. Recently, this coefficient has been applied in the crop model to quantify the growth process of wheat and maize under PM [69]. According to Formula (6), the compensation coefficient is deduced and calculated as follows [104,108]:

$$C_C = \frac{T_{cum-a-NM} - T_{cum-a-PM}}{T_{cum-s-PM} - T_{cum-s-NM}} \quad (15)$$

where $T_{cum-a-NM}$ is the value of GDD_a under NM (°C d); $T_{cum-a-PM}$ is the value of GDD_a under PM (°C d); $T_{cum-s-PM}$ is the value of GDD_s under PM (°C d); and $T_{cum-s-NM}$ is the value of GDD_s under NM (°C d).

For the compensatory coefficient at different growth periods, Equation (15) is modified by considering the growth period as a step [105]:

$$C_c^i = \frac{\left(GDD^i_{a(NM)} - GDD^{i-1}_{a(NM)}\right) - \left(GDD^i_{a(PM)} - GDD^{i-1}_{a(PM)}\right)}{\left(GDD^i_{s(PM)} - GDD^{i-1}_{s(PM)}\right) - \left(GDD^i_{s(NM)} - GDD^{i-1}_{s(NM)}\right)} (i \geq 1) \quad (16)$$

where C_c^i is the compensatory coefficient at growth period i, and $GDD^i_{a(NM)}$ and $GDD^{i-1}_{a(NM)}$ are values of GDD_a under NM at growth period i and $i-1$, respectively (°C d). $GDD^i_{a(PM)}$ and $GDD^{i-1}_{a(PM)}$ are values of GDD_a under MM at growth period i and $i-1$, respectively (°C d). $GDD^i_{s(PM)}$ and $GDD^{i-1}_{s(PM)}$ are values of GDD_s under PM at growth period i and $i-1$, respectively (°C d). $GDD^i_{s(NM)}$ and $GDD^{i-1}_{s(NM)}$ are values of GDD_s under NM at growth period i and $i-1$, respectively (°C d).

Considering the eigenvalues on the logistic curve and the terminal time for the compensatory effect, Equation (15) could also be modified as follows [105]:

$$C_c^j = \frac{t_{j(NM)} - t_{j(PM)}}{\left(GDD^j_{s(PM)} - GDD^{j-1}_{s(PM)}\right) - \left(GDD^j_{s(NM)} - GDD^{j-1}_{s(NM)}\right)} (j \geq 1) \quad (17)$$

where $t_{j(NM)}$ and $t_{j(PM)}$ are the time nodes on the logistic curve under NM and PM, respectively, and coefficient j is 1, 2, or 3. $GDD^j_{s(PM)}$ and $GDD^j_{s(NM)}$ are the values of GDD_s under PM and NM at the same thermal time node of $t_{j(PM)}$, respectively. When j = 1, $GDD^o_{s(PM)}$ and $GDD^0_{a(NM)}$ equal 0 °C d.

For special application conditions, such as the absence of soil temperature data, a linear relationship between soil temperature and air temperature can be used to estimate the soil temperature. Thus, with the above relationship taken into consideration, Equation (17) for winter wheat can be simplified as follows [69]:

$$C_c^j = \frac{t_{j(NM)} - t_{j(PM)}}{0.146 \times \left(t_{j(PM)} - t_{j-1(PM)}\right)} (j \geq 1) \tag{18}$$

For summer maize, Equation (17) can be simplified as follows:

$$C_c^j = \frac{t_{j(NM)} - t_{j(PM)}}{0.111 \times \left(t_{j(PM)} - t_{j-1(PM)}\right)} (j \geq 1) \tag{19}$$

where C_c^j is the compensation coefficient of the accumulated temperature of the film coating in the growth period, and $t_{j(NM)}$ and $t_{j(PM)}$ are the thermal time nodes (°C d) corresponding to the eigenvalues of logistic curves under the open field and film mulching treatments, respectively. In Equations (18) and (19), 0.146 and 0.111 are transfer coefficients for the winter wheat-growing season and the summer maize-growing season, respectively [69].

Presently, the compensatory effect of PM is mainly studied during summer maize, cotton, and winter wheat-growing seasons, and most of the study regions are in the northern arid and semi-arid areas of China (Table 1). The calculation results showed that values of C_c at early growth stages are generally greater than those at late growth stages. The values of C_c differ between years for the same crop because of the influence of climatic factors, geographical locations, soil moisture content, soil microtopography (i.e., different application methods of PM), and other factors.

Table 1. Values of compensation coefficient under plastic mulching.

Crops	Growing Stages	Compensation Coefficient C_c	Experimental Site	Reference
Cotton	at bud stage	0.51	Yuncheng, Shanxi Province	[101]
	from bud stage to flowering stage	0.22		
Cotton	from seedling to trefoil stage	0.371	Shihezi, Xinjiang Province	[104]
	at the trefoil stage	1.345		
	at bud stage	0.207		
	from emergence to bud stage.	0.843		
Maize	from sowing to seedling stage	0.45	Harbin, Heilongjiang Province	[107]
	from seedling to tasseling stage	0.20		
Maize	from sowing to emergence	1.356	Fuxin, Liaoning Province	[108]
	from emergence to tasseling	0.635		
Maize	at seedling stage	0.93 for black film; 1.44 for transparent film	Shenyang, Liaoning Province	[106]
	at jointing stage	1.39 for black film; 1.54 for transparent film		
	at heading stage	0.90 for black film; 0.93 for transparent film		
Maize	from sowing to seedling stage	0.81	Yangling, Shaanxi	[105]
	from seedling to tasseling stage	0.63		
Winter wheat	from sowing to emergence	1.08	Yangling, Shaanxi	[105]
	from emergence to overwintering	0.54		

4.5. Simulation of the Compensatory Effect

Given the compensatory effect under PM, researchers have developed and calibrated the SUCROS-Cotton model [81] and improved the calculation method of the compensatory effect in CERES-Maize and AquaCrop models [63,105,107,108]. At present, in the application of the compensatory effect, existing research is usually based on an empirical method where the increase in soil temperature is converted into the compensatory amount of GDD_a by using the compensation coefficient. In this case, the increase in soil temperature is added to the average air temperature, and then the daily maximum temperature and daily minimum temperature in the crop models are updated. Based on the above calculations, the compensatory effect under PM can be introduced into the crop models by the meteorological input data [63,104,107]. Although this empirical method is simple and convenient, it lacks theoretical basis and does not consider the impact of daily air temperature change on other crop growth parameters in the model. Therefore, the compensatory effect can be considered by further quantifying the influence of the warming effect of PM practices on crop growth and development. Moreover, the module of the compensatory effect under PM practices coupled with existing crop models needs to be established in the future.

5. Implications

5.1. Theoretical Framework for Safe Mulching Period of PM Practices

With the progress of study, the safe mulching duration for PM practices is proposed from the perspective of efficient crop management during crop-growing seasons. That is, the plastic film should stay whole without cracks developing at a time (i.e., the safe mulching duration), in which the PM practice can produce a relatively good agricultural microclimate from conditions of light, temperature, water, and environment in a given region. After the safe mulching duration, the effects of PM practices on crop growth and development can weaken, and even negative effects may be produced on crop physiology, resulting in a low benefit for the farmland ecological environment [130]. The safe mulching duration for PM practices implies the time threshold of PM measures on crop growth and development. Thus, when the PM practice is beyond a certain time limit, the promoting effect of PM practices on crop growth can be significantly weakened and may even have a negative effect.

The safe mulching period of PM practices is preliminarily determined during the growing season of potato in North China and cotton in Xinjiang, respectively [131,132]. In a certain region, clarifying this time threshold can help obtain crops that are of a good quality and high yield, improve the recycling efficiency of PM, and reduce the cost of degradable plastic film [130]. Moreover, determining the time threshold can help the PM technology adapt to the new requirements in ecological construction and economic development in dryland farming when considering the degradable plastic film.

However, previous assessments of the time threshold mainly accounted for external indicators for crop development, such as soil hydrothermal properties and final yields under different mulching durations. Few researchers investigated the mechanism of the time threshold from the crop's internal physiology [131,132]. From the above description of the compensatory effect, its terminal time reflects the time threshold of PM practices acting on the crop's physiological development. We conjecture that some relation may exist between these two concepts. From the action time of PM on plant development, the terminal time of the compensatory effect can be regarded as an extension of the concept of the safe mulching duration of PM. A comparison between the two action windows for the compensatory effect and the safe mulching duration under PM practices shows that the safe mulching duration may be longer than the effective time of the compensatory effect as PM could still conserve soil moisture for crop plant use even after the compensatory effect has ceased. Future studies should focus on the theoretical fusion of the time threshold of the compensatory effect with the safe mulching duration under PM practices. Moreover, clarifying the terminal time of the PM compensatory effect to determine the induction period of degradable film has become an important scientific problem.

5.2. Monitoring and Determination of the Terminal Time

Based on the effect of soil temperature on crop development, the terminal time of the compensatory effect is closely related to the growth process of the plant apical meristem. Quantifying the plant growth processes of apical meristem under PM and NM treatments and then comparing the differences between the processes occurring under these two management systems may be an effective way to determine the terminal time of the compensatory effect. However, some issues need to be handled carefully when the growth process of the apical meristem is used to determine the terminal time. First, the warming effect of PM measures can still affect the near-soil surface air temperature within a certain range after the plant apical meristem is exposed to the air [133], which can extend the value range of the terminal time. Determining the terminal time would become difficult because of the interaction effect between soil temperature and air temperature under PM conditions. Second, PM measures can directly affect the crop root growth, as well as the absorption and transport of water and nutrients by modifying soil temperature and moisture, and then indirectly affect the crop shoot growth [69], which complicates the threshold quantification by various indirect effects of PM measures on plant development. Finally, the change in geographical environment, climate conditions, and crop varieties and the difference in film mulching methods may greatly influence the growth process of crop apical meristem, which would also increase the complexity of the threshold quantification process. Therefore, characteristics of the apical meristem development process should be first accurately captured based on the continuous monitoring of soil moisture, heat, and crop growth indicators. Afterwards, the thermal time with appropriate indices can help quantify key growth stages for plant young ear differentiation and leaf primordium development. The aforementioned factors have an important role in further quantifying the terminal time of the compensatory effect that should be addressed and clarified.

Plant apical meristem and leaf develop in synchrony and harmony [134], and the occurrence rate of crop leaves are mainly dominated by the ambient temperature around the plant apical meristem [116,117]. Therefore, indicators of the leaf initiation process, such as the leaf occurrence rate and the leaf thermal spacing, can be observed accurately and conveniently. Thus, they can be used to further quantify the growth process of apical meristem under PM. Among the critical stages of the plant apical meristem development, the stages of flower primordial formation, two edges, and apical spikelet during the wheat growth seasons [135], and the stages of the growth cone elongation at the young ear growth stage, spikelet differentiation, floret differentiation, and organ development formation during the maize-growing seasons [75], can be used as indicators to characterize and quantify the growth process of apical meristem.

Previous studies related to crop leaf occurrence focused only on the external morphological indicators of crops and seldom on the microscopic development indicators of the plant apical meristem. Few agronomic practices could directly modify crop growth and development processes under PM conditions; thus, relevant studies lack pertinence, and the result of the time range for the key growth stage is broad. Meanwhile, with the continuous renewal and development of crop varieties, the development process of plant apical meristem will be improved accordingly. The original law of plant elongation and development may not be applicable, and further revision of the process and understanding of plant development is urgently needed. In addition, to date, limited studies that focus on leaf development processes involve PM measures [136–138], and the influence of the compensatory effect of PM measures on the crop leaf development process is still unclear. Therefore, the dynamics of the leaf occurrence process, the key stage of apical meristem development, and crop dynamic growth indicators with the crop GDD under PM need to be further studied quantitatively. Afterward, researchers can comprehensively determine the action window of the PM compensatory effect by comparing parameters between PM and NM treatments.

5.3. Module of the Compensatory Effect in Crop Models

Existing studies pay much attention to quantifying the compensatory effect by using the external factors of crop growth, such as the aboveground process and plant height [43,69]. As the action mechanism of the compensatory effect is not fully revealed, current quantitative relations of mathematical equations cannot provide support in building a complete module in crop models. Given this situation, some widely used crop growth models, such as DNDC [44], CERES [45], WHCNS [94,95], and AquaCrop [46], mainly take PM functions into account for restraining soil evaporation and changing energy transfer when involving the effects of PM measures. The actual effects of PM measures on crop growth and development have not been fully considered in crop models. As a result, the optimization and expansion of parameters related to crop growth and development under film mulching conditions are rarely involved.

In the coupled model of RZ-SHAW, the factors of air temperature, photoperiod, the stress of soil moisture and fertilization, and soil temperature during seed germination are employed to modulate the rate of crop growth and development. After crop emergence, the air temperature around the canopy (i.e., GDD_a) becomes the dominant factor for crop growth and development [98,139]. Although RZ-SHAW has considered the warming effect of PM measures on topsoil temperature in terms of energy balance, it can only characterize the warming effect of PM measures to promote crop germination [140]. The continuous influence of the compensatory effect on the plant development process after crop emergence is not involved in the simulation scope. In addition, the parameters of the leaf thermal spacing in the CERES-MAIZE and CERES-WHEAT of RZ-SHAW are supposed to be constant, which could not explain the difference in the leaf occurrence rate between PM and NM treatments.

So far, several parameters in crop models that can interpret the compensatory effect on crop growth and development have greatly limited the accurate simulation of film mulching conditions and their impact on crop development. The influence of soil temperature on crop growth under the condition of film mulching needs to be clarified. Some urgent tasks are to further quantify the compensatory effect of PM, establish mechanism formulas and modules, and incorporate them into the simulation and application of crop models.

6. Conclusions

In this study, we reviewed the warming effect of PM on soil energy transfer and the compensatory effect of PM on crop development to better understand their interactions and uncertainties, and we concluded as follows:

(1) The strength of the warming effect could change with the growth and development of crops, strengthening during the early stage of crop growth and gradually weakening as a crop canopy develops. The warming effect under PM is also affected by local climate conditions, mulching methods, soil depth, film types, and crop categories. Generally, the warming effect has a good promotion effect on crop growth, but the crop growth can be hampered even with a yield reduction when the increased soil temperature caused by PM measures exceeds the tolerant temperature for plant growth.

(2) The compensatory effect of PM could be used to quantify the growth and development of crops under PM and has been widely applied to cotton, corn, winter wheat, and rice. The compensation coefficient is larger in the early stage of crop growth than in the later stage. The compensation coefficient has certain differences for the same crop because of the influence of climate factors, soil moisture content, and soil microtopography.

(3) With the development of the crop canopy, the compensatory effect of PM gradually weakens or even disappears as the solar radiation cannot directly reach the ground after the crop canopy covers the soil. Thus, a prior determination of an effective time threshold is required for applying the compensatory effect of PM. When the cumulative plant height is fitted to a logistic equation, the thermal time (t_m) at the maximum growing rate of the fast-growing stage and the thermal time (t_2) at the end time of the fast-growing stage could be used as the action terminal time during winter wheat- and summer maize-growing seasons, respectively.

(4) From evaluating the soil energy balance under PM, cultivating an understanding of the internal microcosmic and dynamic detailed variation in energy transport processes is the main developing trend of studies and research efforts on specific characteristics. In the future, the theoretical integration of the safety period of PM and the time

threshold of the compensatory effect could be theoretically interpreted; the time threshold of the compensatory effect could be accurately estimated by monitoring the growth and development of the plant apical growth tissue during crop growth seasons; and the construction of the compensatory effect module in the crop models will also be an important issue.

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