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A modified method for pesticide transport and fate in subsurface environment of a winter wheat field of Yangling, China

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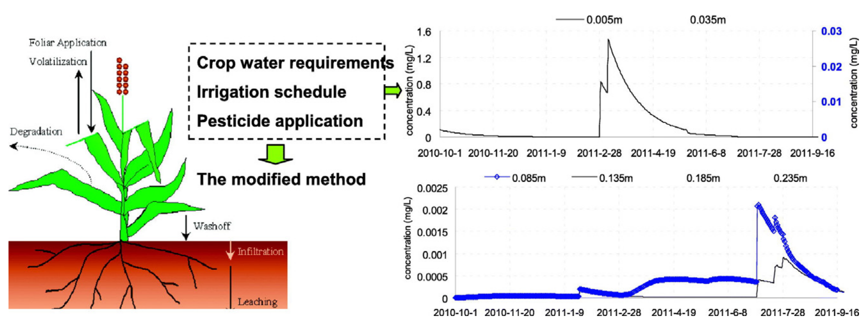
HIGHLIGHTS

- A modified method coupling crop water requirement and pesticide transport was innovatively proposed.
- The effects of irrigation and pesticide application on soil pesticide residues were evaluated.
- Delayed effects of irrigation on pesticide peak are gradually obvious with increase of soil depth.
- One-day interval and five-divided irrigation quota can effectively reduce soil pesticide levels.

GRAPHICAL ABSTRACT



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ABSTRACT

The Guanzhong region is one of the water resources shortage areas and also an important food producing area in Chinese Loess Plateau. The unreasonable application of irrigation and pesticide not only reduces the utilization rate of pesticides, but also is a potential threat to aquatic environments. In order to explore the reasonable application pattern of irrigation and pesticide, a modified method considering crop water requirement and pesticide transport was established to simulate transport and fate of *Triadimefon* in subsurface environment of a winter wheat field in Yangling, China. Results indicate that: (1) the modified method introduces the concepts of crop water requirement and irrigation schedule, which can estimate irrigation amount more accurately and achieve the goal of water saving and agricultural diffuse pollution control more efficiently. The method shows good potential applications and implications in predicting pesticide exposure levels of different crops and in reducing pesticide pollution. (2) The changing trends of soil pesticide levels under different pesticide applications are various. The *Triadimefon* concentration level in surface soil layer (0.005 m) was directly affected by pesticide application and irrigation. The *Triadimefon* peak below the soil depth of 0.035 m has prominently delayed effects and it is mainly affected by irrigations. The concentration of pesticides decays rapidly with the increase of soil depth, and it can be ignored below the depth of 0.5 m. (3) The soil pesticide levels under different pesticide and irrigation modes show considerable differences, the irrigation is still the most significant factor affecting the level of soil pesticide residues under different time intervals between pesticide application and irrigation. The irrigation scheme of one-day interval and five-divided irrigation can effectively reduce deep soil pollution without affecting the normal growth of crops. Results may provide theoretical basis and guide farmers to choose appropriate irrigation and pesticide application patterns.

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1. Introduction

Pesticide application is an important means of increasing agriculture production (Min and Kong, 2016). Most pesticides are roughly sprayed on crops in form of droplets, of which only about 10% are attached to crops, most of which are sprayed in the air, and other parts of the pesticide fall into the soil (Liu and Zhao, 2010; Liu et al., 2013). Pesticides attached on crops are infiltrated into soil under the influence of wind and rain, and pesticides in the atmosphere descend in soil, which increase the amount of pesticide residues and derivatives in soil, and seriously pollute soil (Zhao et al., 2010; Ouyang and Hao, 2016). The pesticides in the soil are washed into rivers, lakes and seas, and become one of the main sources of water pollution (Tao et al., 2010; Ouyang et al., 2016). Irrigation is also an important technical measure to develop agriculture production (Zhan et al., 2011). People often emphasis on one-sided economic benefits brought by irrigation, while seldom consider the negative effects of irrigation on the overall ecological environment of farmland (Song et al., 2001). Pesticides may be transported by irrigation water and soil water to a shallow aquifer through different soil layers, which may lead to soil and groundwater pollution (Zhang and Goh, 2015). Therefore, how to accurately simulate the transport and transformation of pesticides in subsurface environment and how to find a reasonable irrigation and pesticide application pattern are the key to implement the action plan of agricultural diffuse pollution control.

Modeling is one of the most effective tools to study the transport and transformation of pesticide pollutants (Huang et al., 2002; Chu and Mariño, 2007; Chiu et al., 2017). According to the research scale and focus of a model, the pesticide transport model can be generally divided into four categories (Ouyang and Hao, 2016): 1) field scale models, such as PRZM (Pesticide Root Zone Model), which is a 1-dimensional model that simulates pesticide transport in the vertical soil column of the crop root zone (Carsel et al., 1985; Adriaanse et al., 2017); RZWQM (Root Zone Water Quality Model), which simulates water quality and the effects of management practices on crop growth, hydrology, nutrient cycling, organic matter, and chemical losses (Ahuja et al., 1999; Zhang and Goh, 2015); OpusCZ, which simulates water quality and the effects of management practices on crop growth, hydrology, nutrient cycling, organic matter, and chemical losses (Smith, 1992; Zhang and Goh, 2015); CREAMS (Chemicals, runoff, and erosion from agricultural management systems), and GLEAMS (Groundwater loading effects of agricultural management systems, Leonard et al., 1987) etc.; 2) basin scale models, including AnnAGNPS (Annualized agricultural non-point source pollution), HSPF (Hydrologic Simulation Program Fortran), MIKE SHE (Système Hydrologique Européen), SWAT (Soil & Water Assessment Tool, Bannwarth et al., 2014), and APEX (Agricultural Policy/Environmental eXtender) (Mudgal et al., 2010), etc.; 3) static or dynamic river water quality models, including TOXSWA (TOXic substances in Surface WAters), which simulates pesticide behavior in the streams (Adriaanse et al., 2013), WASP (Water quality Analysis Simulation Program), which simulates water quality status in different environmental pollution control system, RWQM (Receiving Water Quality Model), and QUAL2E (enhanced stream water quality model) (Jaworska et al., 2001), etc.; 4) ecological risk assessment model, including SYNOPS-WEB (Strassemeyer et al., 2017), DREAM (distributed model for runoff, evapotranspiration and antecedent soil moisture simulation), and PERPEST (predicts the ecological risks of pesticides) etc. These different kinds of models have various complexities and have undergone a series of improvements, they have been extensively used for studying runoff loads, pesticide concentrations in runoff, fate and transport of agricultural pesticides in soils and overland flow (Reichenberger et al., 2007; Taghavi et al., 2011; Payraudeau and Gregoire, 2012; Wu et al., 2014). In general, not all models used for these assessments were developed specifically for simulating agrochemical transport at all appropriate scales of interest (Bannwarth et al., 2014). Basin scale models simplify the description of pesticide migration processes, but it provides the ability to simulate complex physical, chemical, and biological processes of multiple land use and soil types at the landscape level (Luo and Zhang, 2009). For example, SWAT model uses hydrological simulation and the appropriate design of crop growth and evapotranspiration to achieve the simulation of pesticide environmental behavior in a watershed (Gassman et al., 2007; Holvoet et al., 2008; Gevaert et al., 2008). Although the field scale model cannot simulate the watershed scale, it can analyze the whole process of pesticide migration and transformation more in detail and more in depth (Estes et al., 2015), such as key hydrological processes, crop growth, evapotranspiration, irrigation, pesticide application, plant root uptake, volatilization, adsorption, leaching, degradation, and field management practices and so on (Gagnon et al., 2016). For use in semiarid regions where irrigation is widely applied, models should be capable of simulating pesticide runoff and leakage generated by rainfall and irrigation events (Zhang and Goh, 2015).

The pesticide pollution has characteristics of environmental toxicity and persistence, which is a potential threat to subsurface environment (Chen and Fu, 2000; Chang et al., 2005; Peng, 2011; Zhan et al., 2011). Henderson (1976) thought that the appropriate farmland management (such as: no tillage, irrigation methods, intercropping, pesticide and fertilizer applications) was the most effective and economic method to control agricultural diffuse pollution. The unreasonable irrigations not only cause the leaching loss of pesticide (Zhou and Li, 2001; Chen, 2009), but also affect the growth and yield of crops (Lin et al., 2005; Peng, 2011; CAAS, 2011). Among the large amount of pesticide models available, the irrigations in most of the existing models are simulated by an irrigation simulator (Chu and Mariño, 2007; Zhang and Goh, 2015), for example, the PRZM treated sprinkler irrigation exactly the same as natural rainfall, the RZWQM considered sprinkler irrigation and allowed users to define water input rates and application dates, the OpusCZ simulated both sprinkler and flood irrigation and allowed users to specify the application date and rate of water input (Zhang and Goh, 2015), the SWAT model and the APEX model both have manual and automatic irrigation simulation functions, and they can transfer water from one stream or reservoir to another (Mudgal et al., 2010; Arnold et al., 2012; Rocha et al., 2015). Although the above models are able to design different irrigation patterns, they rarely consider actual crop water requirement during the whole crop growth period. In order to clarify the relationship between irrigation and pesticide transport under natural rainfall conditions, it is very necessary to modify the existing pesticide transport model and study the optimal irrigation and pesticide application mode for achieving the goal of increasing grain production and reducing diffuse pollution of pesticides.

The integrated pesticide transport modeling in a canopy-soil system (IPTM-CS) is able to deal with various pesticide application methods that are commonly used in practice, such as over-canopy spray, under-canopy soil surface spray, soil-incorporated application, and any combination of over- and under-canopy applications (Chu, 2008). Although the built-in automatic irrigation simulators facilitate irrigation scheduling according to soil moisture conditions and a variety of management criteria in terms of water use efficiency and water quality control, it does not give full consideration to crop water requirements during the whole growth cycle of crops, which may lead to insufficient water or unnecessary waste, and may cause pesticide leakage or runoff loss. Therefore, the IPTM-CS model developed by Chu and Mariño (2007) was innovatively coupled with crop water requirement model to study pesticide environmental transport and fate in a winter wheat field of the Guanzhong tableland area. The objectives of this study are to (1) establish a modified method combining pesticide transport model and crop water requirement model, (2) reveal spatiotemporal distribution and transport rules of *Triadimefon* in subsurface environments, (3) evaluate different combination effects of irrigation and pesticide application, (4) determine the optimal irrigation mode and timing arrangement of a winter wheat field. Results may provide scientific reference for the formation of crop–pesticide–soil–water management system in a winter wheat field.