Land use affects the response of soil moisture and soil temperature to environmental factors in the loess hilly region of China

Min Tang[1], Wanning Li[1], Xiaodong Gao[2], Pute Wu[2], Hongchen Li[3], Qiang Ling[4] and Chao Zhang[1]

[1] College of Hydraulic Science and Engineering, Yangzhou University, Yangzhou, Jiangsu, China

[2] Institute of Water-saving Agriculture in Arid Areas of China, Northwest Agriculture and Forestry University, Yangling, Shaanxi, China

[3] School of Resources and Environmental Engineering, Ludong University, Yantai, Shandong, China

[4] College of Environmental and Resource Sciences, Zhejiang A&F University, Hangzhou, Zhejiang, China

Corresponding Author:

Chao Zhang

No. 131 Jiangyang Middle Road, Yangzhou, Jiangsu, 225009, China

Email address: zhangc1700@yzu.edu.cn

Abstract

Changes in soil moisture and soil temperature result from the combined effects of several environmental factors. Scientific determination of the response characteristics of soil moisture and soil temperature to environmental factors is critical for adjusting the sloping land use structure and improving the ecological environment in China's loess hilly region. Soybean sloping fields, maize terraced fields, jujube orchards, and grasslands in the loess hilly region were selected as the research areas. The change in characteristics of soil moisture and soil temperature, as well as their interactions and statistical relationships with meteorological factors, were analyzed using continuously measured soil moisture, soil temperature, and meteorological factors. The results revealed that air temperature and humidity were the main controlling factors affecting soil moisture changes in the 0–60 cm soil layer of soybean sloping fields and grasslands in the normal precipitation year (2014) and the dry year (2015). Humidity and wind speed were the main meteorological factors affecting soil moisture changes in the maize terraced field. Air temperature had a significant negative effect on soil moisture in the jujube orchard. Soil moisture and soil temperature were all negatively correlated under the four sloping land use types. In normal precipitation years, atmospheric humidity had the greatest direct and comprehensive effect on soil moisture in soybean sloping fields, maize terraced fields, and grasslands; soil temperature had a relatively large impact on soil moisture in jujube orchards. The direct and comprehensive effects of soil temperature on soil moisture under all sloping land use types were the largest and most negative in the dry year. Air temperature had a high

38 correlation with soil temperature in the 0–60 cm soil layer under the four sloping land use types,
39 and the grey relational grade decreased as the soil layer deepened. The coefficient of
40 determination between the 0–20 cm soil temperature and air temperature in the maize terraced
41 field was low, indicating a weak response to air temperature. The above findings can serve as a
42 scientific foundation for optimizing sloping land use structures and maximizing the efficient and
43 sustainable utilization of sloping land resources in China's loess hilly region.

Introduction

45 Soil moisture distribution and variability are reflections of and are determined by the interactions
46 between several environmental factors (that might be impacted by human activity) such as
47 climate, vegetation, topography, and soil properties (Zhu et al., 2014; Huang et al., 2016). Soil
48 moisture variability is primarily controlled by a variety of meteorological factors on a time scale
49 (Li et al., 2019; Zhu et al., 2019). For instance, changes in air temperature can influence not only
50 the energy state and availability of soil moisture but also the retention, diffusion capacity, and
51 loss of soil moisture (Pérez, 1998). Precipitation can increase relative humidity in the air and soil
52 moisture content (Chen et al., 2009b). Other meteorological factors, such as wind speed, solar
53 radiation, and water vapor pressure, can also affect the evapotranspiration of soil moisture
54 (Messing et al., 1998). Zhong et al. (2014) found that, in the hilly area of Chongqing, China,
55 temperature, sunshine, and precipitation are inversely correlated with the temporal variation of
56 soil moisture in the 0–10 cm layer from March to May and temperature and sunshine are
57 inversely correlated with the temporal variation of soil moisture in the 0–10 cm layer from June
58 to September. Liu et al. (2021) discovered that the absolute change rate value of soil moisture is
59 positively correlated with air temperature, relative air humidity, and rainfall, but negatively
60 correlated with photosynthetically active radiation, vapor pressure deficits, and wind speed in
61 different subtropical plantations in the Yangtze River Delta region. The response characteristics
62 of soil moisture to meteorological factors are not consistent across different regions because of
63 differences in climate, topography, soil texture, and vegetation. The dominant meteorological
64 drivers for soil moisture variation across different periods are also not consistent. Precipitation,
65 solar radiation, and air temperature are the main factors that affect soil moisture variability in
66 water-scarce areas (Liu et al., 2012a; Wang et al., 2019; Han et al., 2020). Furthermore, air
67 humidity, wind speed, and other factors influence changes in soil moisture by affecting the
68 intensity of soil moisture evaporation (Akinyemi et al., 2007; MacDonald et al., 2018). Soil
69 temperature is another environmental factor that influences soil moisture movement; according
70 to Liu et al. (2020), it directly impacts soil water movement and distribution, and is one of the
71 major influencing factors affecting bare soil evaporation. Soil temperature profile, particularly
72 that of surface soil, varies with seasons and day–night changes in nature and has a direct impact
73 on soil moisture infiltration, redistribution, and evaporation, which is especially significant in
74 arid and semi-arid regions (Sarkar et al., 2007; Sypka et al., 2016).
75   Energy exchange between soil and the atmosphere causes changes in soil temperature
76 owing to the combined effects of solar radiation and precipitation (Meng et al., 2020). Many
77 academics have conducted extensive research on the relationship between changes in soil

78   temperature and meteorological factors and have obtained important findings. According to Hu
79   & Feng (2005), air temperature has a large impact on soil temperature throughout Eurasia across
80   seasons, and precipitation influences soil temperature, particularly at high latitudes and during
81   winter. Sattari et al. (2020) used tree-based hybrid data mining models to estimate soil
82   temperature in Turkey's Sivas Divrigi district, and concluded that sunshine duration and air
83   temperature are key factors in predicting soil temperature, whereas precipitation is the least
84   important meteorological variable. Dodds et al. (2003) investigated the factors influencing soil
85   temperature in pepper fields under plastic mulches, and discovered that mean air temperature and
86   mean radiation, followed by wind speed and relative humidity, were the best predictors of soil
87   temperature, whereas rainfall had little or no effect on it. It can be concluded that differences in
88   the geographic environments and ecological factors of study areas can lead to differences in the
89   effects of the same meteorological factors on soil temperature. Soil temperature is influenced not
90   only by meteorological factors, but also by soil moisture. Moisture and heat in the soil influence
91   and interact with one another, and changes in soil moisture can change the thermal
92   characteristics of the soil, thereby affecting its temperature (Cheng et al., 2013). Mi et al. (2014)
93   discovered that if soil bulk density remains constant during frequent dry–wet alternations, soil
94   moisture has the largest influence on soil thermal parameters, and that the water retention effect
95   of mulching has a direct impact on the dynamic changes in surface soil thermal parameters. In a
96   potato field in Wuchuan County, Inner Mongolia, China, Zhang et al. (2020) discovered an
97   inversely proportional relationship between soil moisture and temperature across treatments
98   which had various water levels.

99   Soil moisture and temperature respond differently to environmental factors depending on
100   the land use type in each region. For instance, according to Hao et al. (2019), converting the
101   vegetation of an area from grasses to evergreen woody plants prolongs the impact of
102   meteorological drought on soil moisture. Therefore, restoring prairies that have been heavily
103   encroached on by woody species may mitigate the impact of climate change on water resources
104   in the transition zone of the United States. Chen et al. (2022) studied the response of soil
105   moisture to precipitation under three typical land-use patterns in the Maowusu Desert of Ningxia,
106   China, and found that the wet front of sand had the fastest response and the largest infiltration
107   depth when compared with a grassland and shrub land. In the grassland, the soil water content
108   fluctuated greatly and the cumulative infiltration amount was large, whereas, in the shrubland,
109   the response of soil water content to rainfall events was relatively stable, and the infiltration
110   amount was the lowest among the three (Chen et al., 2022). Chen et al. (2009a) found that
111   although the soil temperature in winter wheat fields in the North China Plain under different
112   tillage methods (plowing, rotary tillage, and no-tillage with straw mulching) significantly
113   responded to air temperature changes, indicating that the tillage methods affected the range of
114   change of soil temperature. Sun et al. (2016) studied the change in soil temperature and its
115   response to different air temperatures under various irrigation modes in the Inner Mongolia
116   Hetao Irrigation District and found that the temperature of the soil where drip irrigation was
117   practiced under plastic film responded more quickly to changes in air temperature than that

118 where surface irrigation was practiced. They also found that the soil temperature where drip
119 irrigation was practiced under plastic film was higher than that where surface irrigation was
120 practiced at the seedling stage of maize. Under the specific bio-climatic conditions in the loess
121 hilly region, complex and changeable landform types, deep loess, and various types of soil have
122 developed from it. In particular, with the implementation of a project to revert farmland to
123 forestland and grassland, a variety of vegetation types and land use patterns have been developed
124 in the region, such as large areas of arable land mainly planted with maize, potatoes, soybeans,
125 etc.; grasslands from farmlands conversion; and scattered woodlands (jujube orchards, *Caragana*
126 *microphylla* woodlands, *Robinia pseudoacacia* woodlands, etc.), all of which have had
127 considerable effects on soil moisture and temperature in the region. Currently, there are few
128 studies on how soil moisture and temperature respond to environmental factors under various
129 land use types, and the response of soil moisture and temperature to environmental factors needs
130 to be clarified.

131   Therefore, our study investigated four typical land use types in the loess hilly region
132 (soybean sloping field, maize terraced field, jujube orchard, and grassland). Pearson correlation,
133 path, stepwise regression, and grey relational analyses were used to study the relationship
134 between changes in soil moisture and temperature and major meteorological factors
135 (temperature, humidity, solar radiation, wind speed, and precipitation) under different levels of
136 annual precipitation for the four land use types, as well as the relationship between soil moisture
137 and temperature. The goal of this research is to uncover the mechanisms by which various
138 environmental factors influence soil moisture and temperature under different land use types to
139 provide a scientific foundation to improve land use and enable vegetation restoration in the loess
140 hilly region.

Materials & Methods

Overview of the study area

143 The study area was located in the Yuanzegou watershed (37°14′ N, 118°21′ E), Qingjian
144 County (Fig. 1), Shaanxi Province, China, in the north-central part of the Loess Plateau, which is
145 a typical loess hilly and gully area. The study area has a temperate continental monsoon climate,
146 with an annual average air temperature of 8.6°C. January experiences the lowest monthly
147 average air temperature of -6.5°C, while July has the highest monthly average air temperature of
148 22.8°C. The average annual precipitation is 505 mm, but it is unevenly distributed throughout the
149 year, with 70% of the precipitation occurring between July and September. The soil in the study
150 area is loessial (which is comprised of largely silt, followed by sand, and then clay) and has a
151 high infiltration capacity. The field capacity and wilting moisture content are approximately 25%
152 and 7% (volumetric moisture content), respectively. The precipitation in the growing season
153 (from May to October) in 2014 and 2015 was 377.4 mm and 289.2 mm (Fig. 2), respectively,
154 and 2014 and 2015 were considered a normal precipitation year and a dry year, respectively,
155 according to Hao et al. (2003).

Experimental scheme

157 Considering the above-mentioned land use types and vegetation characteristics in the study area,
158 soybean sloping fields, maize terraced fields, jujube orchards, and grasslands with similar slope
159 aspects (shady slopes) and gradients (approximately 18°) were selected as the experimental plots
160 (Fig. 3). Soybean and maize were sown at densities of $19.5×10^4$ and $9×10^4$ plants·hm^{-2},
161 respectively, in late April and early May each year, and both were harvested in early October.
162 Lizao was the jujube species used in the experiment. It had been planted in 2003 and was in the
163 full-bearing period during the experiment. Plant spacing was 2 m, and row spacing was 3 m. The
164 grassland has been naturally restored from sloping farmland for more than 30 years ago. The
165 eugenic plant was *Artemisia gmelinii* and the associated plants were *Lespedeza daurica* (Laxm.)
166 Schindl. and *Bothriochloa ischaemum* (L.) Keng. During the experiment, none of the plots were
167 irrigated, and field management followed the local standard. The soil properties of the different
168 sloping land use types are listed in Table 1.
169 Data were collected as previously described in Zhang et al. (2022). Specifically, two sets of
170 automatic soil moisture and temperature monitoring instruments were installed in the middle of
171 each experimental plot along the same contour line with a 10-meter interval in April 2014. The
172 monitoring points in the soybean sloping field and maize terraced field were placed between crop
173 rows, and the jujube orchard monitoring points were placed 30 cm away from the trunks of the
174 jujube trees. In this study, an EC-5 soil moisture sensor (Decagon Devices Inc., Pullman, WA,
175 USA) was used to measure soil volumetric water content (VWC). Compared with traditional soil
176 moisture sensors, such as the Hydra Probe and Theta Probe, EC-5 soil moisture sensors are
177 economical dielectric sensors suitable for regional research. The soil volumetric water content
178 can be calculated by quickly measuring the soil dielectric constant. It has a high-frequency
179 signature that significantly reduces the influence of electroconductibility and soil texture on its
180 readings and is suitable for all soil types. In addition, the high measurement frequency improves
181 the sensor's accuracy (±2% VWC) and range (0-100% VWC). It can realize fast, accurate, and
182 continuous monitoring of soil moisture and is currently widely used in the real-time monitoring
183 of soil moisture (Deveci et al., 2019; Lei et al., 2020). The RR-7110 soil temperature sensor
184 (Rainroot Scientific Ltd., Peking, CN) was used to measure soil temperature. Compared to
185 traditional soil temperature sensors, the RR-7110 soil temperature sensor is easy to connect and
186 install. It is suitable for continuous monitoring of both wild and harsh environments. It has low
187 power consumption and has the function of automatic data saving when powered off, and also
188 has high measurement accuracy (± 0.2°C) and resolution (0.02°C); it is therefore widely used in
189 soil heat monitoring in agriculture, forestry, ecology and other fields (Duan et al., 2018; Ma et
190 al., 2021). The probes for the soil moisture sensor were placed at depths of 10, 20, 60, 100, and
191 160 cm. The probes for the soil temperature sensor were placed at depths of 10, 20, 40, 60, and
192 100 cm. During the vegetation growing season (May to October) in 2014 and 2015, soil moisture
193 and temperature were measured every 2 min, and the data were recorded every 10 min. To
194 characterize the soil moisture and temperature at a certain depth under each sloping land use
195 type, we averaged the soil moisture and temperature at the same depth at the two monitoring
196 points under this sloping land use type. An AR5 automatic weather station (Avolon Scientific

197 Inc., Jersey City, NJ, USA) continuously monitored weather variables, such as temperature,
198 humidity, pressure, solar radiation, wind speed, and precipitation in the study area.

199 **Data processing**

200 *Path analysis*

201 Statistical path analysis was used to decompose the correlation coefficients. Its importance lies
202 not only in revealing the direct and indirect influence of x_i on y in correlation analysis of multiple
203 independent variables x_1, x_2,..., x_m, y, but also in obtaining the path information of the best
204 influence on y from the relationship between an independent variable and other independent
205 variables in a complex correlation between x_1, x_2,..., x_m, y. Therefore, the absolute value of the
206 path coefficient can be used to directly compare the key role of each independent variable in the
207 regression equation, which is of great practical value for clarifying key factors and changing the
208 reflection of dependent variables in a multivariable system. Overall, path analysis is more
209 comprehensive and delicate than correlation analysis. SPSS linear regression was used to
210 perform the path analysis in this study. Please refer to Du & Chen (2010) for more information
211 on the specific procedures. It is worth noting that this study used stepwise regression to create a
212 linear regression equation and then calculated the path coefficient. Stepwise regression has the
213 advantage of gradually adding or removing an independent variable from all available
214 independent variables until the best regression equation is obtained.

215 *Grey relational analysis*

216 The basic principle of grey relational analysis (GRA) is to compare the geometric relationships
217 of statistical sequences to determine the closeness of multiple factors in the system (i.e., grey
218 relational grade). The greater the grey relational grade, the closer the geometric shape of the
219 sequence curves, and vice versa. GRA has an advantage over traditional statistical analysis or
220 other analysis methods in that it analyzes factors based on their development trends, does not
221 specify the sample size, does not require a typical distribution law, has a small calculation
222 amount, and provides calculation results that are consistent with qualitative analysis results.

223   Before performing GRA, the reference sequence must first be determined, followed by a
224 comparison of the similarity of the other sequences to the reference sequence. If the reference
225 sequence is $X_0=\{X_0(k)|k=1,2,\ldots,n\}$, and the comparison sequence is
226 $X_i=\{X_i(k)|k=1,2,\ldots,n\}(i=1,2,\ldots,m)$, then the correlation coefficients of $X_i(k)$ and $X_0(k)$ are
227 calculated as follows:

$$\varepsilon_i(k) = \frac{min_i min_k|x_0(k) - x_i(k)| + \rho max_i max_k|x_0(k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho max_i max_k|x_0(k) - x_i(k)|} \tag{1}$$

229   where ρ is the resolution coefficient and is usually 0.5; $|x_0(k)-x_i(k)|$ is the absolute difference
230 between X_0 and the k-th index of X_i; $min_i min_k|x_0(k) - x_i(k)|$ and $max_i max_k|x_0(k) - x_i(k)|$ are
231 the two-level minimum and maximum differences, respectively.

232   The following formula can be used to calculate the correlation coefficient between $X_i(k)$ and
233 $X_0(k)$.

$$\varepsilon_i(k) = \{\varepsilon_i(k) \,\big|\, k = 1,2,...,n\} \tag{2}$$

235   The correlation coefficient value of each comparison and reference sequence at each point
236   is obtained from the correlation coefficient calculation. There are numerous outcomes and the
237   data are dispersed. As a result, the correlation coefficient of each comparison sequence at each
238   point must be collectively reflected in one value, which is the grey relational grade $r(x_0, x_i)$ of the
239   comparison sequence to the reference sequence, commonly abbreviated as r_i. The average
240   method is the most commonly used method for calculating the grey relational grade, and the
241   formula is as follows:

242
$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\varepsilon_i(k) \tag{3}$$

243   The grey relational grade is as previously described by Zhang et al. (2021). Specifically, the
244   grey relational grade in this study reflects the proximity of each influencing factor to soil
245   temperature. The greater the grey relational grade, and the closer it is to 1, the closer the
246   connection between the reference sequence and the comparison sequence, and the greater the
247   influence of the comparison sequence on the reference sequence, and vice versa. When the grey
248   relational grade is greater than 0.80, the factors corresponding to the comparison sequence are
249   thought to be closely related to soil temperature and have a large impact. The soil temperatures
250   of the surface layer (0–20 cm), middle layer (20–60 cm), and deep layer (60–100 cm) in the four
251   experimental sloping land use types were used as parameter variables. To determine the effects
252   of air temperature, air humidity, solar radiation, wind speed, precipitation, and soil moisture on
253   soil temperature under various sloping land use types, the reference sequence and each
254   environmental factor sequence were quantified using dimensionless equations, and the grey
255   relational coefficients between each environmental factor sequence and the reference sequence
256   were calculated.

257   **Data analysis**

258   Binary correlation analysis between soil moisture and environmental factors was performed
259   using the Pearson correlation analysis method in SPSS software (SPSS Inc., Chicago, Illinois,
260   USA). The stepwise regression method in SPSS was used to screen the independent variables in
261   the stepwise regression analysis of the environmental factors affecting soil moisture, and the
262   variables that met the allowable level (0.05) were entered into the model. Drawing was
263   performed using OriginPro 2017 software (OriginLab Corp., Northampton, MA, USA).

264   # Results

265   **Soil moisture response to environmental factors**

266   *Binary correlation analysis between soil moisture and environmental factors*
267   According to previous research (Tang et al., 2019a), the soil moisture in the 0–60 cm soil layer
268   fluctuated greatly during the growing season, and the soil moisture in the 60–160 cm soil layer
269   altered uniformly under various experimental sloping land use types. It can be concluded that
270   environmental factors had a significant impact on soil moisture in the 0–60 cm soil layer. Table 2
271   shows the correlation analysis results for daily mean moisture content in the 0–60 cm soil layer
272   and daily mean air temperature (x_1), daily mean air humidity (x_2), daily mean solar radiation (x_3),

273   daily mean wind speed (x_4), daily precipitation (x_5), and daily mean soil temperature in the 0–60

274   cm soil layer (x_6) under the four experimental sloping land use types.

275   During the 2014 growing season, soil moisture in the 0–60 cm soil layer of the soybean

276   sloping field was significantly correlated with air temperature, air humidity, and wind speed,

277   with the correlation between soil moisture, air temperature, and air humidity reaching a

278   significant level ($p<0.01$) (Table 2). In the 2015 growing season, the soil moisture of the soybean

279   sloping field was significantly correlated with the air temperature, air humidity, and solar

280   radiation ($p<0.01$). It can be concluded that, whether in a normal precipitation year or a dry year,

281   air temperature and humidity were the main controlling factors for soil moisture changes in the

282   soybean sloping field at a small catchment scale. The soil moisture of the maize terraced field

283   was significantly correlated with air temperature, humidity, and wind speed ($p<0.01$) during the

284   2014 growing season. The correlations between soil moisture in the maize terraced field and air

285   humidity, wind speed, and precipitation were significant ($p<0.01$) during the 2015 growing

286   season. Based on the findings, air humidity and wind speed were the most important controlling

287   factors affecting soil moisture changes in the maize terraced field on a regional scale during

288   various levels of annual precipitation. In the 2014 growing season, soil moisture of the jujube

289   orchard was significantly correlated with air temperature, air humidity, and precipitation;

290   however, in the 2015 growing season, it was only significantly correlated with air temperature

291   and wind speed ($p<0.01$). In both growing seasons, the correlation between soil moisture in the

292   jujube orchard and air temperature was significant ($p<0.01$), indicating that among the

293   meteorological factors studied, air temperature had a significant impact on soil moisture in the

294   jujube orchard (i.e., soil moisture decreased as air temperature rose). During the 2014 and 2015

295   growing seasons, the correlation between soil moisture, air temperature, and air humidity in the

296   grassland reached a significant level ($p<0.01$), indicating that air temperature and air humidity

297   were the main factors affecting the change in soil moisture in the grassland, regardless of

298   precipitation differences. In the growing seasons of 2014 and 2015, air temperature, solar

299   radiation, and wind speed were negatively correlated with soil moisture under the four sloping

300   land use types. This was due to increased air temperature, solar radiation, and wind speed, which

301   resulted in increased soil evaporation, which subsequently resulted in a decrease in the moisture

302   content in the 0–60 cm soil layer. Under various sloping land use types, air humidity and

303   precipitation were positively correlated with soil moisture, indicating that as air humidity and

304   precipitation increased, soil moisture also increased.

305   In the 2014 and 2015 growing seasons, there was a negative correlation between soil

306   moisture and soil temperature in the 0–60 cm soil layer under various sloping land use types. All

307   of them were found to be statistically significance ($p<0.01$) (Table 2), indicating that soil

308   moisture and soil temperature affected each other in this soil layer, and as the soil temperature

309   increased, the soil moisture decreased. The dry year showed a substantially higher correlation

310   between soil moisture and soil temperature in the 0–60 cm soil layer under the same sloping land

311   use type as compared to that in the normal precipitation year. This could be because the dry year

312   experienced a severe soil water shortage, and the high soil temperature in the 0–60 cm soil layer

313 increased soil moisture evaporation, resulting in a strong negative correlation between soil
314 temperature and soil moisture. In the 2014 and 2015 growing seasons, a lower correlation
315 between soil moisture and soil temperature in the 0–60 cm soil layer was found in the maize
316 terraced field than in the other three sloping land use types. This is because the soil temperature
317 of the 0–60 cm soil layer in the maize terraced field was relatively low, and the average soil
318 temperature of this soil layer did not exceed 20℃ in the two growing seasons (i.e., soil moisture
319 evaporation was minimal). Similarly, the average soil temperature of the 0–60 cm soil layer in
320 the jujube orchard was 20.73℃ in the 2014 growing season, which was 0.41, 1.20, and 1.81℃
321 higher than that of the soybean sloping field, maize terraced field, and grassland, respectively.
322 The evaporation of soil moisture in this soil layer was accelerated by the higher soil temperature
323 in the jujube orchard, causing the soil temperature to have a strong negative effect on soil
324 moisture.
325 *Path analysis of the relationship between soil moisture and environmental variables*
326 It is easy to overlook the interaction between environmental factors only by judging their
327 contribution of environmental factors to soil moisture based on the simple correlation coefficient
328 between environmental factors and soil moisture. The correlation coefficients between various
329 environmental factors and soil moisture were divided into direct and indirect effects for path
330 analysis, to further explore the direct and indirect effects of various environmental factors on soil
331 moisture.
332   In the 2014 growing season, air humidity had the greatest direct effect on soil moisture in
333 the 0–60 cm soil layer of the soybean sloping field, maize terraced field, and grassland, with
334 direct path coefficients of 0.492, 0.491, and 0.716, respectively, followed by solar radiation
335 (Table 3). Soil temperature had the greatest direct effect on soil moisture in the jujube orchard,
336 with a direct path coefficient of -1.101. The direct influence of air humidity and solar radiation
337 on soil moisture under the four sloping land use types showed positive effects. The direct impact
338 of soil temperature on soil moisture in soybean sloping fields, jujube orchards, and grasslands
339 was negative. The absolute value of the direct path coefficient of soil temperature in the soybean
340 sloping field and grassland was greater than the absolute value of the sum of indirect path
341 coefficients. The sum of indirect effect coefficients of soil temperature was very small,
342 indicating that the influence of soil temperature on the soil moisture of the soybean sloping field
343 and grassland in the 0–60 cm soil layer was mainly reflected in the direct effect. The evaporation
344 of soil moisture in the soybean sloping field and grassland intensified as the soil temperature
345 increased, reducing the moisture content in the 0–60 cm soil layer. As a result, the impact of soil
346 temperature on soil moisture was primarily a direct effect, with little correlation to other
347 meteorological factors. The absolute values of the direct path coefficients of air temperature, air
348 humidity, and wind speed were greater than the absolute value of the sum of their respective
349 indirect path coefficients in the maize terraced field. The sum of these three meteorological
350 factors' respective indirect path coefficients was small, indicating that the influence of these
351 three meteorological factors on the soil moisture of the 0–60 cm soil layer of the maize terraced
352 field was mainly reflected in the direct effect. The evaporation capacity of the atmosphere

353 increased as the air temperature increased, and the increase in wind speed aided the increase in
354 the evaporation rate. Because of the aforementioned comprehensive factors, soil evaporation
355 increased in the maize terraced field, reducing the moisture content of the 0–60 cm soil layer. As
356 a result, the influence of air temperature and wind speed on soil moisture was mainly a direct
357 effect, and the correlation with other environmental factors was weak. Soil evaporation
358 decreased as air humidity increased and the rate of soil moisture loss slowed. It has a direct
359 influence on soil moisture, with little correlation with other influencing factors. Although solar
360 radiation had a large direct effect on soil moisture under the four sloping land use types, all of
361 which had coefficients above 0.4, it also had a relatively large indirect effect on soil moisture
362 through other environmental factors (such as air temperature, air humidity, and soil temperature),
363 resulting in a small overall impact of solar radiation on soil moisture. Therefore, the simple
364 correlation coefficients between solar radiation and soil moisture under various sloping land use
365 types were low.
366   Soil temperature had the greatest direct impact on soil moisture in the 0–60 cm soil layer
367 under the soybean sloping field, maize terraced field, jujube orchard, and grassland in the 2015
368 growing season, with direct path coefficients of -0.762, -0.861, -0.950, and -0.741, respectively,
369 all of which had negative effects (Table 4). The soil moisture of the soybean sloping field, jujube
370 orchard, and grassland was positively affected by air humidity. The direct path coefficients of
371 soil temperature under soybean sloping fields and grasslands were greater than the sum of
372 indirect path coefficients, and the sum of indirect path coefficients of soil temperature was very
373 low (-0.017), indicating that the influence of soil temperature on soil moisture under these two
374 sloping land use types was mainly reflected in the direct effect, with little correlation with other
375 meteorological factors. The evaporation of soil moisture was accelerated by an increase in soil
376 temperature, resulting in soil moisture loss and decline. The direct effect (0.193) of air humidity
377 on soil moisture in jujube orchards was opposite to the comprehensive indirect effect (-0.166) on
378 soil moisture through the influence of air temperature, wind speed, and soil temperature. The
379 simple correlation coefficient between air humidity and soil moisture in jujube orchards was as
380 low as 0.027 owing to the superposition of the two effects, indicating that atmospheric humidity
381 had negligible effect on the change in soil moisture in jujube orchards and that it was
382 unnecessary to consider too much. The direct effect of air temperature on soil moisture in the
383 maize terraced field and jujube orchard was positive; however, the indirect effect on soil
384 moisture by influencing wind speed and soil temperature was negative, and the indirect path
385 coefficient was approximately 1.5 times that of the direct path coefficient. The comprehensive
386 effect of air temperature on soil moisture in the maize terraced field and jujube orchard was
387 negative, as predicted by its indirect effect.
388 *Environmental factors affecting soil moisture: a stepwise regression analysis*
389 The effects of different independent variables on the dependent variable can be explained using
390 multiple stepwise regression analyses. Therefore, the dependent variable in this study was soil
391 moisture (y) in the 0–60 cm soil layer under various sloping land use types, and the independent
392 variables were air temperature (x_1), air humidity (x_2), solar radiation (x_3), wind speed (x_4),

393   precipitation (x_5), and soil temperature (x_6) in the 0–60 cm soil layer. The main environmental
394   factors affecting soil moisture were investigated using multiple stepwise regression analysis.
395   Empirical models were developed based on the final regression results to predict the soil
396   moisture content in the 0–60 cm soil layer under different sloping land use types (Table 5).
397   The regression equations for various sloping land use types reached extremely significant
398   levels ($p<0.01$) during the 2014 and 2015 growing seasons (Table 5). Different environmental
399   factors were entered into the stepwise regression model for different sloping land use types in
400   different precipitation years. In the 2014 growing season, the contribution rates of air humidity
401   and solar radiation to soil moisture under the soybean sloping field, maize terraced field, and
402   grassland were higher than those of other environmental factors; the total contribution rates of air
403   humidity and solar radiation to soil moisture were 70.91% for soybean sloping fields, 67.48% for
404   maize terraced fields, and 74.68% for grasslands. The results showed that air humidity and solar
405   radiation were the main controlling factors affecting soil moisture in the soybean sloping field,
406   maize terraced field, and grassland during the 2014 growing season. In the jujube orchard, soil
407   temperature contributed more to soil moisture (35.87%) than air temperature, air humidity, or
408   solar radiation, indicating that the relationship between soil temperature and soil moisture in the
409   0–60 cm soil layer was closer in the 2014 growing season. During the 2015 growing season, soil
410   temperature was entered into the regression equation of soil moisture in the 0–60 cm soil layer
411   under four sloping land use types, and the contribution rate of soil temperature to soil moisture
412   under all sloping land use types was more than 49%, with more than 81% for soybean sloping
413   fields and grasslands. Soil temperature had a significant effect on soil moisture change under
414   various land use types in the dry year, and it was the main controlling factor of soil moisture
415   change in soybean sloping fields and grasslands, according to the findings. The sum of air
416   temperature and soil temperature contributions to soil moisture in the maize terraced field and
417   jujube orchard was 86.45% and 78.29%, respectively, indicating that air temperature and soil
418   temperature were the main factors affecting soil moisture changes in the 0–60 cm soil layer of
419   these two sloping land use types.

420   **Response of soil temperature to changes in environmental factors**

421   The GRA was used in this study to examine the impact of different environmental factors on soil
422   temperature, with soil temperature as the dependent variable and air temperature, air humidity,
423   solar radiation, wind speed, precipitation, and soil moisture as the independent variables. The
424   main factors influencing soil temperature were then screened for four different sloping land use
425   types.

426   *GRA on the main influencing factors of soil temperature*

427   The grey relational grade between environmental factors and soil temperature is shown in Table
428   6 for different sloping land use types. The grey relational grade between air temperature and soil
429   temperature in the surface and middle layers under the four sloping land use types was the
430   highest, ranging from 0.8275 to 0.8446, according to the standard grey relational grade being
431   greater than or equal to 0.80, indicating that air temperature was the primary factor affecting soil
432   temperature in the 0–60 cm soil layer under various sloping land use types. The upper soil layer

433 increased the barrier between the lower soil layer and the environment as the soil depth
434 increased, and the grey relational grade between the soil temperature and air temperature
435 decreased. Using the 2014 growing season as an example, the grey relational grade between the
436 soil temperature in the surface layer and air temperature in the soybean sloping field, maize
437 terraced field, jujube orchard, and grassland was 0.8439, 0.8444, 0.8398, and 0.8417,
438 respectively, whereas the grey relational grade in the middle layer decreased to 0.8394, 0.8388,
439 0.8318, respectively, and 0.8395, indicating that the grey relational grade decreased with the
440 deepening of the soil layer. Furthermore, solar radiation had a significant impact on the soil
441 temperature in the surface layer under the soybean sloping field and jujube orchard, with grey
442 relational grades of 0.8107 and 0.8006, respectively. During the 2014 growing season, the grey
443 relational grade between soil temperature in the deep layer and air humidity was at its highest,
444 with values of 0.8344, 0.8352, and 0.8356, under the soybean sloping field, maize terraced field,
445 and grassland, respectively. Wind speed was closely related to soil temperature in the deep layer
446 of the soybean sloping field, maize terraced field, and grassland in the 2015 growing season,
447 with the grey relational grade exceeding 0.82, indicating that wind speed had a significant impact
448 on soil temperature in the 60–100 cm soil layer under these three sloping land use types. Air
449 temperature was the most crucial factor affecting soil temperature in the deep layer of the jujube
450 orchard during the 2014 and 2015 growing seasons. The grey relational grade between
451 precipitation and soil temperature in the surface layer and deep layer under the four sloping land
452 use types was the lowest in the 2014 growing season, with the grey relational grade in the surface
453 layer ranging from 0.5233 to 0.5605 and the grey relational grade in the deep layer not exceeding
454 0.6305, indicating that precipitation had insignificant effect on soil temperature in the 0–20 cm
455 and 60–100 cm soil layers. The average grey relational grade between wind speed and soil
456 temperature in the middle layer under the four sloping land use types was as low as 0.54,
457 indicating that it was not closely related to the soil temperature in the 20–60 cm soil layer. The
458 grey relational grades of precipitation, air humidity, solar radiation, and soil temperature in the
459 surface, middle, and deep layers under various sloping land use types in the 2015 growing season
460 were all low, with average grey relational grades of 0.6161, 0.5980, and 0.5856, respectively,
461 indicating that precipitation, air humidity, and solar radiation had little effect on soil temperature
462 in the 0–20 cm, 20–60 cm, and 60–100 cm soil layers.
463   There were differences in the grey relational grade between the soil temperature in the same
464 soil layer and the same environmental factor under different sloping land use types and the same
465 external meteorological conditions (Table 6), which may be caused by differences in the
466 underlying surface of the four sloping land use types. When it comes to solar radiation, for
467 example, the more vegetation on the underlying surface, the less solar radiation the ground
468 receives, and the slower the soil's response to solar heating. Furthermore, the greater the surface
469 roughness of the underlying surface, the lower the surface albedo and the easier it is to absorb
470 solar radiation. It can be concluded that sloping land use influences the energy exchange between
471 meteorological factors and soil, resulting in different responses of soil temperature to
472 meteorological factors. The distribution and changes in soil moisture, as well as soil temperature,

473 are affected by differences in the properties of the underlying surface under various sloping land
474 use types.

Soil temperature response characteristics to air temperature

476 According to the findings, air temperature had a significant impact on soil temperature under
477 various experimental sloping land use types, particularly in the 0–60 cm soil layer. The
478 correlation between soil temperature and air temperature at different depths was investigated
479 using average data from daily observations, as shown in Fig. 4.

480 The coefficient of determination (R^2) between air temperature and soil temperature in the
481 surface layer under the four sloping land use types ranged from 0.72 to 0.91 in the 2014 and
482 2015 growing seasons (Fig. 4), indicating a strong correlation. The highest R^2 in the middle and
483 deep layers did not exceed 0.68 and 0.30, respectively, and the lowest was as low as 0.32 and
484 0.01. This shows that, as the soil layer depth increased, the correlation between air temperature
485 and soil temperature decreased, implying that the time it took for the change in soil temperature
486 to catch up to the change in air temperature increased. It is worth noting that the maximum R^2
487 between the soil and air temperature in the deep layer was less than 0.30, indicating that the deep
488 layer's response to air temperature was rather weak. The primary cause of this phenomenon is
489 that solar radiation heats the surface soil, which is then transferred to deep soil via heat
490 conduction and convection. As the depth of the soil layer increased, the heat carried by
491 conduction and convection decreased, causing the soil temperature to decrease. As a result, air
492 temperature changes had a significant impact on the surface soil but not on the deep soil.

493 The R^2 between the soil temperature in the surface layer and the air temperature in the
494 jujube orchard and grassland in the 2014 growing season was approximately 0.83, which was
495 lower than that in the soybean sloping field, and the R^2 in the maize terraced field was relatively
496 low, approximately 0.72 (Fig. 4). In the 2015 growing season, the coefficients of determination
497 between the soil temperature in the surface layer and air temperature in the soybean sloping field,
498 jujube orchard, and grassland were all around 0.90, which was higher than that in the maize
499 terraced field.

Discussion

The link between changes in soil moisture and environmental factors

502 The combined effects of multiple influencing factors, such as land use (vegetation, topography,
503 etc.), meteorological factors (precipitation, air temperature, wind speed, etc.), and soil properties,
504 result in temporal and spatial changes in soil moisture. Soil moisture retention, diffusion, and
505 loss can all be impacted by rising air temperatures (Qiu & Ben-Asher, 2010; Chen et al., 2018).
506 Precipitation can increase atmospheric relative humidity and soil moisture content, while solar
507 radiation and wind speed can influence the evaporation of soil moisture. Changes in soil
508 temperature have a significant impact on soil moisture, affecting both the maintenance and
509 movement of soil moisture. Cho & Choi (2014) investigated the temporal and spatial variability
510 of soil moisture and its relationship with meteorological factors at the regional scale of the
511 Korean Peninsula and found that soil moisture was positively correlated with daily average
512 precipitation but negatively correlated with air temperature. Czarnecka & Nidzgorska-Lencewicz

513 (2006) found that the variability of soil moisture to a depth of 10 cm under rye and potato
514 cultivation is mainly due to total precipitation levels. Moisture in deeper soil layers under rye
515 depends primarily on air humidity, and under potato cultivation, on the thermal conditions of air
516 and soil. In an oasis farmland-shelter forest, Wang (2007) discovered a significant negative
517 correlation between wind speed and soil moisture, but no significant influence of solar radiation,
518 air temperature, or atmospheric relative humidity on soil moisture content. Han et al. (2016)
519 analyzed soil moisture and temperature data from four Qaidam Basin sampling sites and found
520 that soil temperature was closely related to soil moisture, and the relationship between soil
521 temperature and moisture at various depths at the Nomhon site was a quadratic function with a
522 parabolic change. The relationship between soil temperature and moisture in the shallow layer
523 was also quadratic at the Delingha and Da Qaidam sites, whereas the soil temperature and
524 moisture in the deep layer were positively linearly correlated. The soil moisture in the 0–60 cm
525 soil layer under different sloping land use types responded differently to environmental factors in
526 this study (Tables 2, 3, 4, and 5), primarily because of differences in vegetation types and
527 coverage, as well as micro-topography, which directly affected the ground receiving
528 precipitation and solar radiation, as well as the meteorological environment near the ground. In
529 general, soil moisture was positively correlated with precipitation and air humidity, whereas it
530 was negatively correlated with air temperature, wind speed, solar radiation, and soil temperature
531 (Table 2). The results of this study differ slightly from those of previous studies, which could be
532 due to the different regions studied (such as humid, arid, and semi-arid regions), as well as the
533 study's scale and time (Wang et al., 2016; Baldwin et al., 2017).

534   The direct and comprehensive effects of air humidity on soil moisture in the 0–60 cm soil
535 layer under soybean sloping fields, maize terraced fields, and grasslands were at their peak in the
536 2014 growing season, according to the path analysis results (Table 3). In the jujube orchard, soil
537 temperature in the 0–60 cm soil layer had a significant impact on soil moisture (Table 3). The
538 direct and comprehensive effects of soil temperature on soil moisture under various sloping land
539 use types were greatest during the 2015 growing season (Table 4). This is because increased
540 plant transpiration and soil evaporation result from lower air humidity and higher soil
541 temperature, resulting in a decrease in the soil moisture content (Li et al., 2002; Kidron &
542 Kronenfeld, 2016). The environmental variables entered for the four sloping land use types in the
543 2014 and 2015 growing seasons were air temperature, air humidity, solar radiation, wind speed,
544 and soil temperature in the 0–60 cm soil layer, according to the stepwise regression analysis in
545 this study (Table 5). The above results differ from the findings of Zhang et al. (2013); that is, the
546 daily mean air temperature was included in the input variable in this study, while it was excluded
547 from Zhang et al.'s research results and did not enter the input variable. The difference in input
548 variables is due to the difference in study area and time, and the direct effect of air temperature
549 on soil moisture in Zhang et al.'s study was small, with a direct path coefficient of only -0.0364,
550 and the comprehensive determination ability of air temperature on soil moisture was small. The
551 air temperature was entered into the regression model of the soil moisture under the maize
552 terraced field and jujube orchard in this study during the 2014 and 2015 growing seasons (Table

553 5), especially in the dry year, where the direct path coefficient between the air temperature and
554 the soil moisture under the maize terraced field and jujube orchard was both greater than 0.54
555 (Table 4). Although the indirect effect of air temperature on soil moisture through other
556 environmental factors (air humidity, wind speed, and soil temperature) was the opposite of the
557 direct effect, the combined effect of air temperature on soil moisture under these two sloping
558 land use types was still relatively large (Table 4). This may be because the soil in the jujube
559 orchard is exposed over a large area, and the change in soil moisture is mainly affected by
560 evapotranspiration, while the change in air temperature changes the atmospheric evaporative
561 force, resulting in changes in soil evaporation and jujube transpiration (Li et al., 2018).
562 Compared with the other three sloping land use types, terraced fields reduce the ground slope,
563 change the original topography, flatten the field surface, avoid the generation of runoff, and store
564 rainwater, increase infiltration, and improve soil moisture through interception, which has been
565 confirmed in previous studies by the authors and others (Tang et al., 2019a, b; Xu et al., 2021).
566 High soil moisture content implies that there is sufficient water in the soil for evaporation, and
567 evaporation changes are mainly affected by air temperature changes (Kohfahl et al., 2021).
568 Therefore, soil moisture in the maize terraced field was closely related to air temperature. Air
569 temperature did not enter the soil moisture regression model of soybean sloping fields and
570 grasslands in the 2014 and 2015 growing seasons (Table 5), indicating that the effect of air
571 temperature on soil moisture was weak and almost negligible. This may be because the leaf area
572 index and coverage of soybean and natural grass are higher than those of jujube orchards with
573 large areas of bare soil, and the vegetation covers the soil surface intensively, which hinders the
574 exchange of water vapor and heat in the soil with the outside air and weakens the response of soil
575 moisture change to air temperature. In addition, the sum of the indirect path coefficients of solar
576 radiation under the soybean sloping field, maize terraced field, and grassland in the 2014
577 growing season was high, with values of -0.442, -0.467, and -0.581, respectively (Table 3). The
578 absolute value of the indirect path coefficient of solar radiation affecting soil moisture through
579 air temperature, air humidity, and soil temperature was above 0.384, and the maximum value
580 was as high as 0.603 (Table 3), indicating that solar radiation had a substantial impact on soil
581 moisture through air temperature, air humidity, and soil temperature, according to the
582 composition of the indirect path coefficient of solar radiation.

583 **Soil temperature changes in response to environmental factors**

584 Numerous studies have shown that air temperature is the most important meteorological factor
585 that affects soil temperature (Paul et al., 2004; Wan et al., 2007). The grey relational grade
586 between air temperature and soil temperature in the 0–60 cm soil layer under the four sloping
587 land use types was found to be the highest in this study, ranging from 0.8275 to 0.8446 (Table 6),
588 indicating that air temperature was the primary factor affecting the soil temperature of the 0–60
589 cm soil layer under different sloping land use types. The grey relational grade between soil and
590 air temperature decreased as the soil depth increased (Table 6), indicating that the influence of
591 soil temperature on air temperature weakened as the soil depth increased. As a result, during the
592 2014 and 2015 growing seasons, air temperature was not the primary driver of soil temperature

593 change in the 60–100 cm soil layer under soybean sloping fields, maize terraced fields, and
594 grasslands. However, in the 60–100 cm soil layer of the jujube orchard, air temperature was still
595 the most important factor influencing soil temperature, and it could be because the jujube
596 orchard is exposed and the vegetation coverage is low, resulting in poor ground shading.
597 However, the soil moisture content in the 60–100 cm soil layer of the jujube orchard was low,
598 and many pores in the soil were filled with air. Water has a specific heat capacity of
599 approximately three times that of air, which means that the temperature of water rising or falling
600 is approximately one-third that of air when absorbing or releasing the same heat. As a result, the
601 lower the soil moisture content, the weaker the regulating effect on soil temperature and the
602 easier it is for external meteorological conditions to affect soil temperature. Owing to the
603 aforementioned two factors, air temperature has a significant impact on the deep soil of the
604 jujube orchard.

605   The coefficient of determination between soil temperature and air temperature in different
606 soil layers of 0–100 cm under the four sloping land use types was different in the study of the
607 response of soil temperature to air temperature (Fig. 4), and the coefficient of determination in
608 the surface layer under the maize terraced field was small (Figs. 4c-4g), indicating that the
609 response was weak. This could be because the plants in soybean sloping fields and grasslands are
610 short, whereas maize plants in terraced fields are tall, and the densely covered maize canopy can
611 intercept a large amount of solar radiation. At the same time, owing to low chlorophyll
612 concentration and a waxy layer on the surface of the leaves, maize leaves have a higher
613 reflectivity than soybean leaves, according to Liu et al. (2012b). In addition, the author's
614 previous research found that the water storage and moisture retention effects of terraced fields
615 were quite significant compared with sloping fields; therefore, the soil moisture content in the 0–
616 20 cm soil layer of the maize terraced field was higher than that of the other three sloping land
617 use types in the 2014 and 2015 growing seasons (Tang et al., 2019a). Water has a much higher
618 specific heat capacity (4.2×10^3 J/(kg·°C)) than soil (1×10^3–2.5×10^3 J/(kg·°C)), which means
619 that the temperature of water rises less than that of soil when they absorb the same amount of
620 heat, whereas the ability of water to lose heat during the cooling process is lower than that of
621 soil. Therefore, the soil specific heat capacity increases as soil moisture content increases, and
622 the higher the soil moisture content, the slower the soil temperature rises and falls, and the less
623 sensitive it is to air temperature. Based on the above results and considering the fact that the
624 loess hilly region has many sloping fields, a wide area of dry land, and low precipitation
625 utilization, it is encouraged to transform sloping fields into terraced fields, strengthen the
626 construction of terraced fields, promote water storage and moisture conservation, enhance soil
627 and water conservation capacity, and alleviate drought and soil erosion. Therefore, it is of great
628 significance to promote the sustainable development of agricultural production in arid areas.

Conclusions

630   (1) Air temperature and humidity were the main factors affecting soil moisture changes in
631 soybean sloping fields and grasslands during the 2014 and 2015 growing seasons. The most
632 important meteorological factors affecting changes in soil moisture in the maize terraced field

633 were air humidity and wind speed. In the jujube orchard, the effect of air temperature on soil
634 moisture was significant ($p<0.01$) and negative. For all sloping land use types, there was a
635 negative correlation between soil moisture and soil temperature in the 0–60 cm soil layer
636 ($p<0.01$). Air humidity had the greatest direct and comprehensive impact on soil moisture in
637 soybean sloping fields, maize terraced fields, and grasslands during the growing season of the
638 normal precipitation year (2014). Soil temperature had a relatively large effect on soil moisture
639 in jujube orchards, and the impact on soil moisture in soybean sloping fields and grasslands was
640 mostly reflected in the direct effect. The direct effects of air temperature, air humidity, and wind
641 speed on soil moisture in the maize terraced field were predominant. The direct and
642 comprehensive effects of soil temperature on soil moisture of various sloping land use types
643 were the largest and showed a negative effect during the growing season of the dry year.

644   (2) In the four sloping land use types, air temperature had a strong correlation with the soil
645 temperature of the 0–60 cm soil layer during the 2014 and 2015 growing seasons, especially in
646 the 0–20 cm soil layer. The correlation was the highest, and the grey relational grade and
647 correlation both decreased as soil depth increased. The soil temperature in the 0–20 cm soil layer
648 under the maize terraced field had the weakest response to air temperature. Air temperature was
649 the most important factor affecting soil temperature in the 60–100 cm soil layer of the jujube
650 orchard.

651   (3) The maize terraced field had favorable effect on soil moisture conservation and soil
652 temperature regulation; therefore, it is encouraged to transform sloping fields into terraced fields
653 in the loess hilly region to improve the efficient use of natural precipitation and promote the
654 sustainable use and improvement of sloping fields.

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Figure 1

Geographical location of the study area.

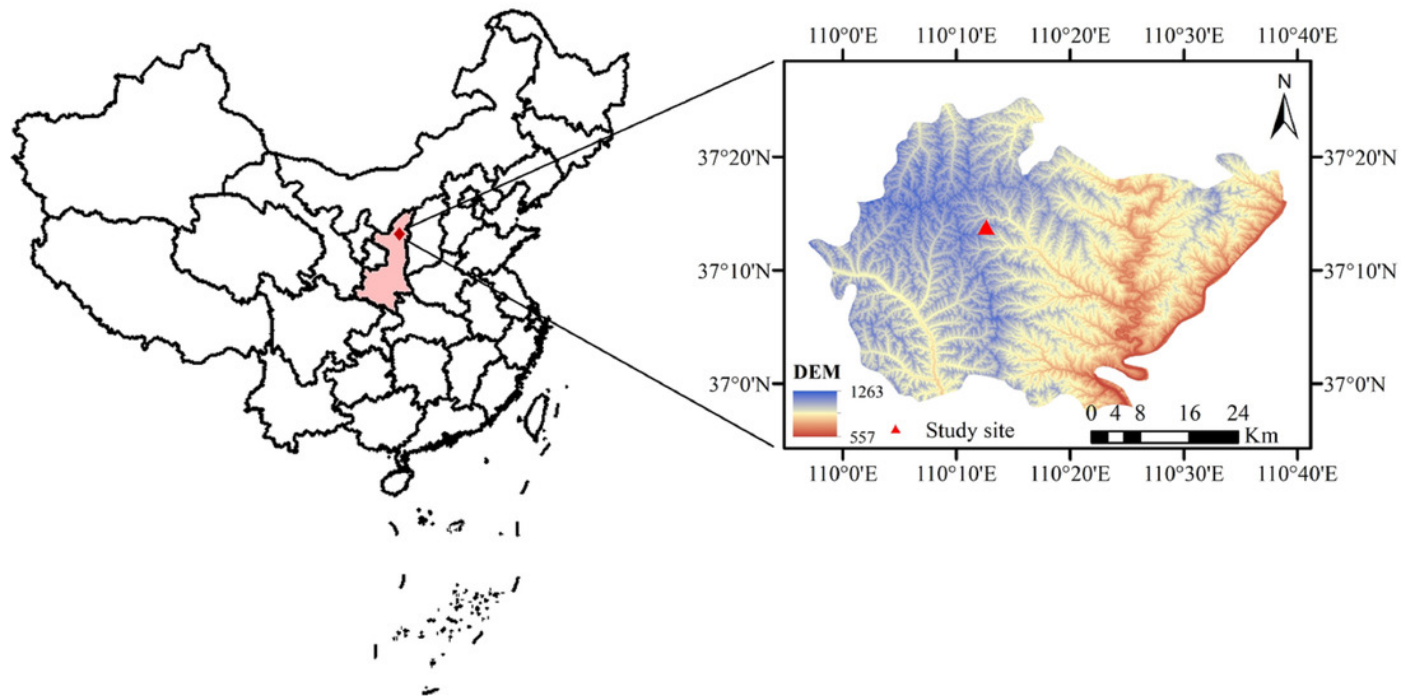



Figure 2

Monthly precipitation and monthly mean air temperature during the 2014 and 2015 growing seasons in the study area.

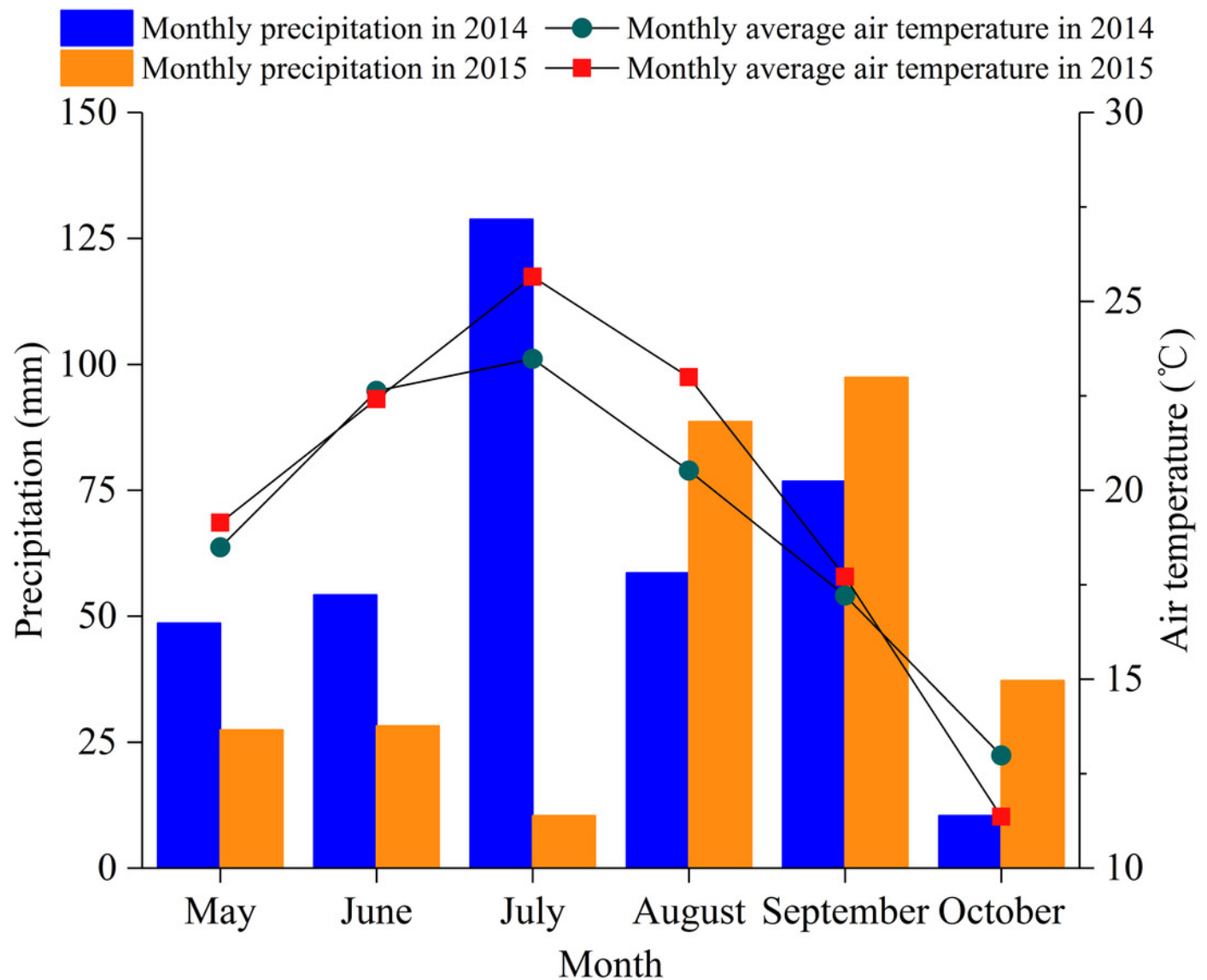



Figure 3

Distribution of land use types and experimental plots in the study area.

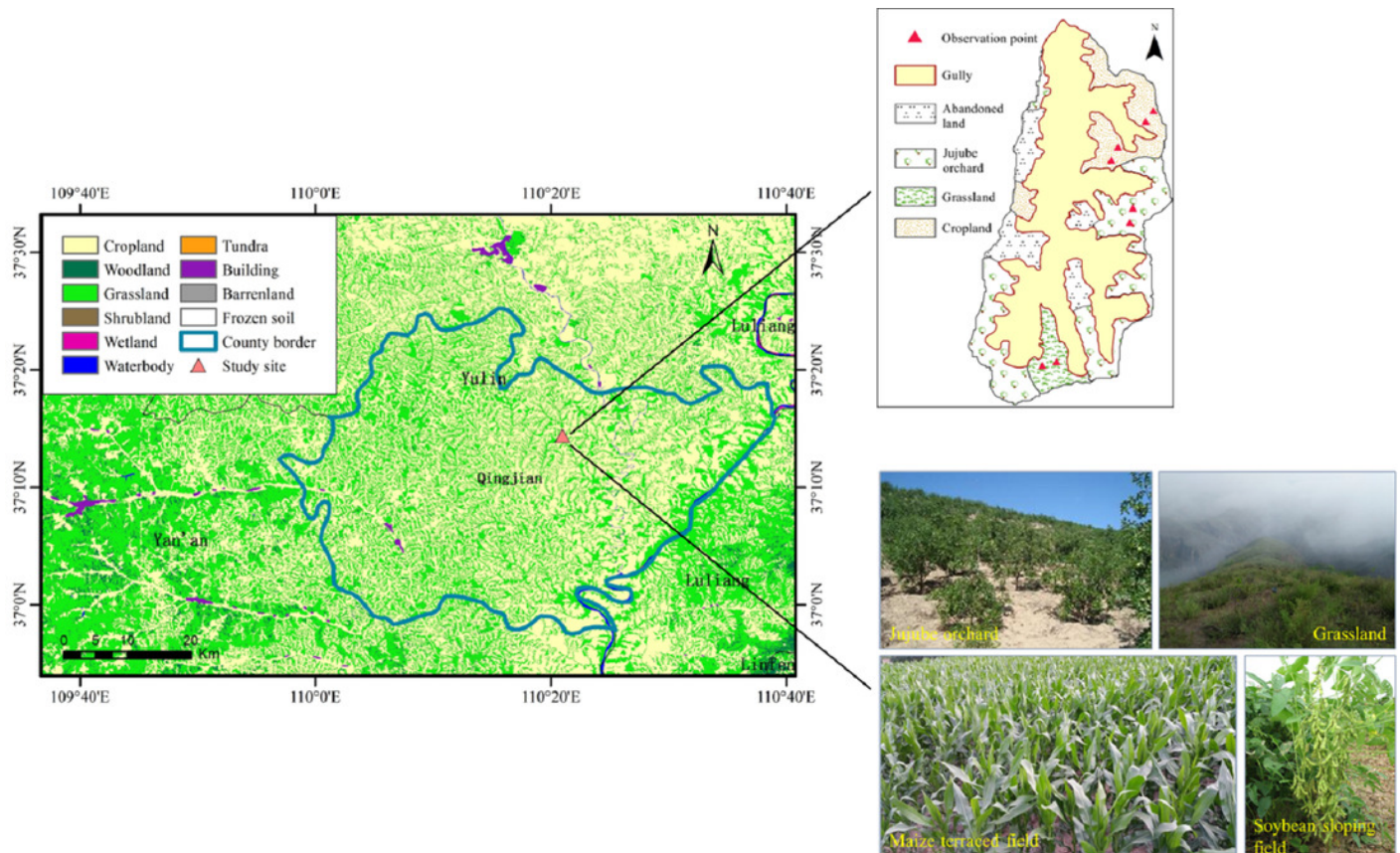
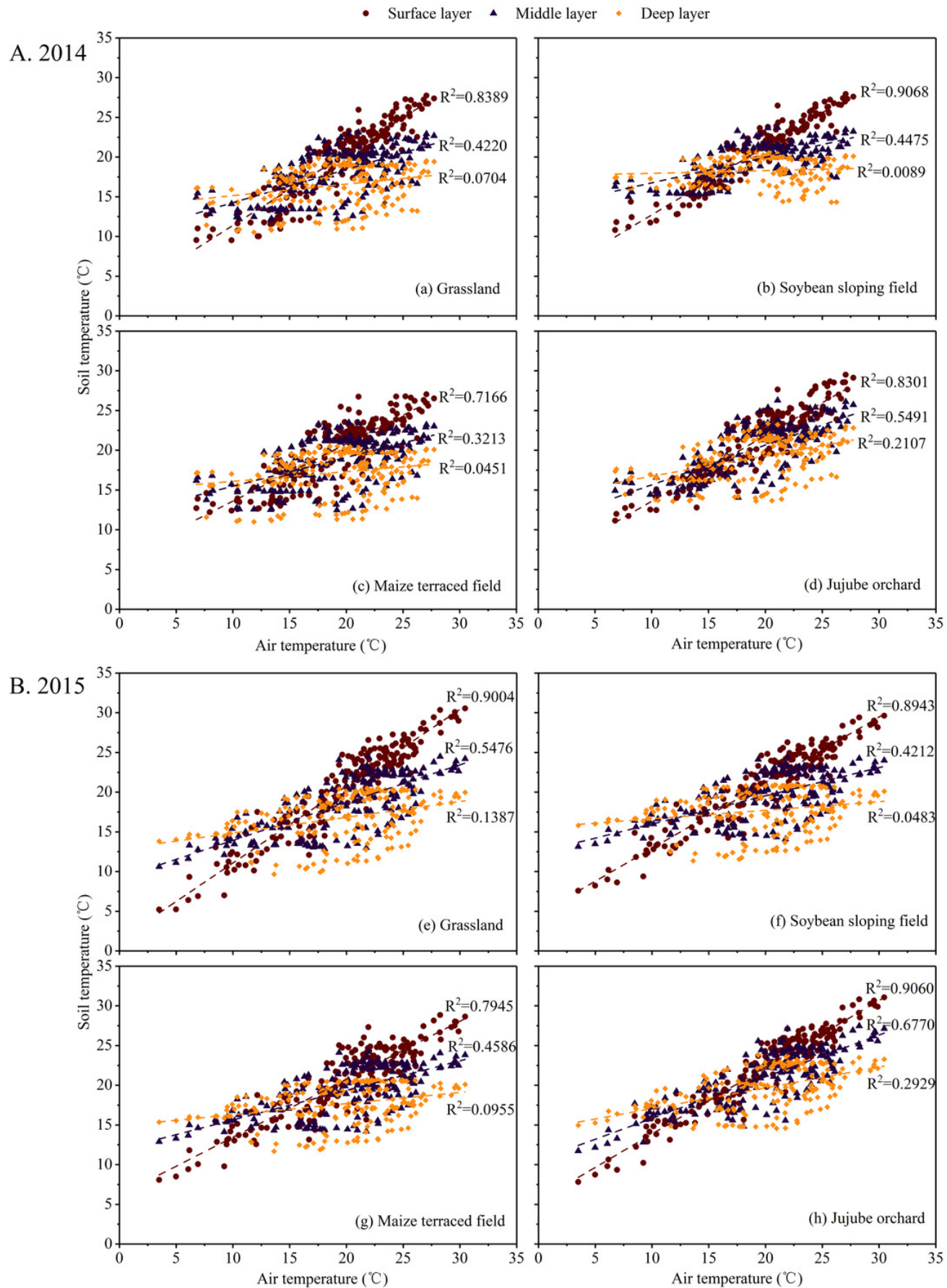



Figure 4

Correlations between soil temperature and air temperature at different soil depths in the experimental land-use types during the 2014 and 2015 growing seasons.

Soil physical properties and nutrient content of experimental plots.

1 **Table 1 Soil physical properties and nutrient content of experimental plots.**

Sloping land use type	Soil layer /cm	Soil texture			Bulk density /(g·cm⁻³)	Soil porosity /%	Saturated hydraulic conductivity /(cm·d⁻¹)	Organic matter /(g·kg⁻¹)	Total N/(g·kg⁻¹)
		Sand/%	Silt/%	Clay/%					
Grassland	0-20	17.3±2.8	63.6±1.3	19.1±3.4	1.28±0.09	54.0±3.4	35.3±8.3	5.12±0.79	0.34±0.04
	20-40	15.1±1.7	62.9±1.6	22.0±0.7	1.28±0.04	52.1±1.5		4.43±0.28	0.28±0.04
	40-60	14.9±3.7	63.3±1.3	21.8±3.8	—	—		4.23±0.36	0.28±0.06
Soybean sloping field	0-20	21.0±5.6	63.0±3.7	16.0±3.9	1.17±0.15	58.9±5.6	74.2±20.6	3.34±0.24	0.29±0.02
	20-40	19.5±5.4	63.4±2.4	17.0±4.5	1.29±0.11	54.3±3.7		2.66±0.31	0.22±0.04
	40-60	19.9±3.9	65.0±1.9	15.1±3.2	—	—		2.52±0.38	0.20±0.02
Maize terraced field	0-20	17.7±1.9	63.8±2.3	18.5±2.9	1.26±0.11	55.1±4.2	55.6±10.4	4.24±0.37	0.30±0.03
	20-40	16.6±3.9	64.9±1.7	18.6±4.1	1.36±0.07	52.5±2.7		2.98±0.33	0.22±0.03
	40-60	16.2±4.1	63.3±1.1	20.5±4.2	—	—		2.74±0.42	0.20±0.03
Jujube orchard	0-20	23.7±4.0	62.6±1.9	13.7±2.4	1.31±0.12	51.7±4.5	36.6±9.6	3.64±0.85	0.31±0.06
	20-40	21.6±3.4	64.0±1.9	14.4±2.7	1.41±0.10	52.1±3.8		2.76±0.89	0.26±0.05
	40-60	20.7±2.2	64.2±1.2	15.1±2.5	—	—		2.60±0.66	0.27±0.05

2 The sampling date is September 5, 2014. Data are mean ± SD, *n*=3. Soil particle composition: Sand% (0.02-2 mm), Silt% (0.002-
3 0.02 mm), and Clay% (<0.002 mm).

Correlation analysis between soil moisture in 0-60 cm soil layer and main environmental factors under experimental sloping land use types.

1 **Table 2 Correlation analysis between soil moisture in 0-60 cm soil layer and main environmental factors**
2 **under experimental sloping land use types.**

Year	Sloping land use type	Environmental factor					
		x_1	x_2	x_3	x_4	x_5	x_6
2014	Grassland	-0.422**	0.511**	-0.151	-0.222**	0.217**	-0.322**
	Soybean sloping field	-0.294**	0.324**	-0.031	-0.174*	0.15	-0.305**
	Maize terraced field	-0.242**	0.402**	-0.035	-0.265**	0.145	-0.224**
	Jujube orchard	-0.289**	0.361**	-0.003	-0.157	0.172*	-0.378**
2015	Grassland	-0.698**	0.227**	-0.334**	-0.111	0.003	-0.758**
	Soybean sloping field	-0.747**	0.246**	-0.384**	-0.058	0.025	-0.779**
	Maize terraced field	-0.152	0.282**	-0.131	0.375**	0.198**	-0.431**
	Jujube orchard	-0.411**	0.027	-0.075	0.245**	0.025	-0.520**

3 x_1: daily mean air temperature; x_2: daily mean air humidity; x_3: daily mean solar radiation; x_4: daily mean wind speed; x_5: daily
4 precipitation; x_6: daily mean soil temperature in the 0-60 cm soil layer; *: significance at 0.05 level; **: significance at 0.01 level;
5 similarly hereinafter.

Path analysis of influencing factors on soil moisture in 0-60 cm soil layer under different sloping land use types in the 2014 growing season.

1 **Table 3 Path analysis of influencing factors on soil moisture in 0-60 cm soil layer under different sloping**
2 **land use types in the 2014 growing season.**

Sloping land use type	Environmental factor	Simple correlation coefficient with y	Direct path coefficient	Indirect path coefficient					
				x_1	x_2	x_3	x_4	x_6	Total
Grassland	x_2	0.511	0.716			-0.603		-0.139	-0.205
	x_3	-0.151	0.429		-0.603			0.384	-0.581
	x_6	-0.322	-0.388		-0.139	0.384			0.065
Soybean sloping field	x_2	0.324	0.492			-0.593		-0.207	-0.167
	x_3	-0.031	0.411		-0.593			0.406	-0.442
	x_6	-0.305	-0.370		-0.207	0.406			0.065
Maize terraced field	x_1	-0.242	-0.266		-0.476	0.591	-0.014		0.024
	x_2	0.402	0.491	-0.476		-0.603	-0.249		-0.089
	x_3	-0.035	0.432	0.591	-0.603		0.075		-0.467
	x_4	-0.265	-0.179	-0.014	-0.249	0.075			-0.086
Jujube orchard	x_1	-0.289	0.801		-0.477	0.597		0.899	-1.090
	x_2	0.361	0.742	-0.477		-0.605		-0.234	-0.382
	x_3	-0.003	0.425	0.597	-0.605			0.415	-0.428
	x_6	-0.378	-1.101	0.899	-0.234	0.415			0.723

Path analysis of influencing factors on soil moisture in 0-60 cm soil layer under different sloping land use types in the 2015 growing season.

1 **Table 4 Path analysis of influencing factors on soil moisture in 0-60 cm soil layer under different sloping**
2 **land use types in the 2015 growing season.**

Sloping land use type	Environmental factor	Simple correlation coefficient with y	Direct path coefficient	Indirect path coefficient				
				x_1	x_2	x_4	x_6	Total
Grassland	x_2	0.227	0.130				-0.131	0.097
	x_6	-0.758	-0.741		-0.131			-0.017
Soybean sloping field	x_2	0.246	0.173				-0.096	0.073
	x_6	-0.779	-0.762		-0.096			-0.017
Maize terraced field	x_1	-0.152	0.576			-0.064	0.830	-0.729
	x_4	0.375	0.225	-0.064			-0.217	0.150
	x_6	-0.431	-0.861	0.830		-0.217		0.429
Jujube orchard	x_1	-0.411	0.549		-0.403	-0.065	0.913	-0.960
	x_2	0.027	0.193	-0.403		-0.505	-0.177	-0.166
	x_4	0.245	0.223	-0.065	-0.505		-0.163	0.022
	x_6	-0.520	-0.950	0.913	-0.177	-0.163		0.431

Stepwise regression analysis of environmental factors affecting soil moisture.

Table 5 Stepwise regression analysis of environmental factors affecting soil moisture.

Year	Sloping land use type	Multiple regression equation	n	F	p	Total variance explained /%
2014	Grassland	$y=11.997+0.086\,x_2+0.012\,x_3-0.234\,x_6$	157	37.834	0.000**	x_2 (46.68), x_3 (28.00), x_6 (25.32)
	Soybean sloping field	$y=13.187+0.059\,x_2+0.011\,x_3-0.256\,x_6$	156	17.774	0.000**	x_2 (38.61), x_3 (32.30), x_6 (29.09)
	Maize terraced field	$y=14.117-0.069\,x_1+0.033\,x_2+0.007\,x_3-0.629\,x_4$	157	15.823	0.000**	x_1 (19.45), x_2 (35.92), x_3 (31.56), x_4 (13.07)
	Jujube orchard	$y=9.989+0.392\,x_1+0.095\,x_2+0.012\,x_3-0.724\,x_6$	150	29.740	0.001**	x_1 (26.09), x_2 (24.18), x_3 (13.86), x_6 (35.87)
2015	Grassland	$y=17.222+0.014\,x_2-0.393\,x_6$	184	130.999	0.000**	x_2 (14.89), x_6 (85.11)
	Soybean sloping field	$y=17.946+0.019\,x_2-0.469\,x_6$	184	158.103	0.000**	x_2 (18.49), x_6 (81.51)
	Maize terraced field	$y=14.698+0.119\,x_1+0.550\,x_4-0.268\,x_6$	184	34.696	0.000**	x_1 (34.67), x_4 (13.56), x_6 (51.78)
	Jujube orchard	$y=10.964+0.156\,x_1+0.014\,x_2+0.749\,x_4-0.361\,x_6$	184	21.896	0.000**	x_1 (28.66), x_2 (10.06), x_4 (11.65), x_6 (49.63)

Grey relational grade between different environmental factors and soil temperature.

1 **Table 6 Grey relational grade between different environmental factors and soil temperature.**

Year	Sloping land use type	Soil layer (cm)	Environmental factor					
			Air temperature	Air humidity	Solar radiation	Wind speed	Precipitation	Soil moisture
2014	Grassland	0-20	0.8417	0.6916	0.7977	0.6218	0.5233	0.7327
		20-60	0.8395	0.6342	0.7889	0.5349	0.6713	0.7081
		60-100	0.6819	0.8356	0.6673	0.7302	0.5679	0.6826
	Soybean sloping field	0-20	0.8439	0.7150	0.8107	0.6249	0.5317	0.7450
		20-60	0.8394	0.6479	0.7742	0.5482	0.6763	0.7040
		60-100	0.6530	0.8344	0.6816	0.7258	0.6305	0.6725
	Maize terraced field	0-20	0.8444	0.6750	0.7952	0.6254	0.5342	0.7132
		20-60	0.8388	0.7083	0.7847	0.5257	0.6742	0.6566
		60-100	0.6670	0.8352	0.6857	0.6938	0.6102	0.7293
	Jujube orchard	0-20	0.8398	0.6864	0.8006	0.6098	0.5605	0.7433
		20-60	0.8318	0.6888	0.6989	0.5522	0.6177	0.7884
		60-100	0.8319	0.7644	0.7069	0.6787	0.5712	0.6419
2015	Grassland	0-20	0.8379	0.6796	0.6992	0.6639	0.6091	0.7271
		20-60	0.8284	0.5574	0.6736	0.6849	0.6608	0.7000
		60-100	0.7002	0.6768	0.5840	0.8235	0.5968	0.7015
	Soybean sloping field	0-20	0.8446	0.6879	0.7102	0.6757	0.6012	0.7411
		20-60	0.8282	0.5711	0.6820	0.6853	0.6452	0.7003
		60-100	0.6562	0.7032	0.5656	0.8268	0.5910	0.6973
	Maize terraced field	0-20	0.8439	0.6753	0.7202	0.6824	0.6060	0.7039
		20-60	0.8301	0.6453	0.6836	0.6970	0.6711	0.7010
		60-100	0.6977	0.6745	0.5834	0.8248	0.6542	0.7098
	Jujube orchard	0-20	0.8320	0.6973	0.7192	0.6780	0.6482	0.7389
		20-60	0.8275	0.6180	0.7111	0.6841	0.6824	0.7125
		60-100	0.8240	0.6716	0.6094	0.6776	0.6186	0.7022