# INCREASING SLOPE STABILITY BY USING EXTERNAL-SOIL SPRAY SEEDING TECHNOLOGY: A REVIEW

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**Abstract.** External-soil spray seeding technology is a widely used method for ecological slope protection, playing a significant role in mitigating soil erosion, landslides, and other geological challenges. However, research on the technical stability of external-soil spray seeding is limited, resulting in suboptimal protective effects and hindering broader application. This review highlights emerging research themes for advancing ecological slope stability, including: ecological substrate, vegetated ecosystem, the mechanical properties and hydrological characteristics of the external-soil spray seeding technology. The review identifies new research themes for developing futuristic ecological slopes can be summarized as: (1) whether or not to find the stability models on the shear strength and bond strength of the substrate under water saturation, (2) how to establish models with the effect of grassland ratio, slope angle, seeding amount, and planting season on the long-term growth of ecological slope protection, (3) how to improve quantitative mechanical models between the roots and soil, (4) how to propose the relevant analytical and numerical methods for root-soil-atmosphere. The findings offer valuable guidelines for improving ecological slope stability and advancing the application of external-soil spray seeding technology.
**Keywords:** *ecological protection, external-soil spray seeding, vegetated slope protection, slope stability, root*

## Introduction

China is currently experiencing a surge in infrastructure development, including highways, railways, and hydropower projects, resulting in numerous exposed rock slopes. The removal of original vegetation exposes bare surfaces, exacerbating soil erosion and increasing the risk of landslides. Thus, the effective prevention of geological disasters in infrastructure engineering has become a critical challenge. External-soil spray seeding technology is widely applied in highways, railways, hydropower, and mining projects to restore and protect rock slopes.

Geotechnical Engineering Association proposed the concept of external-soil spray seeding technology for the first time in 2005, emphasizing that the ecological substrate of external-soil spray seeding technology should be able to expand the green effect, increase slope stability and reduce environmental load, to achieve the aim of human-nature sustainable development (Qian et al., 2022). Scholars have proposed the definition of external-soil spray seeding technology as follows: on the basis of the geological and climatic conditions of the slope, the ecological substrate mainly composed of cementing materials, guest soil, amendments and slope protection seeds is sprayed onto the slope surface to form the base material layer, which is achieved the slope ecological restoration


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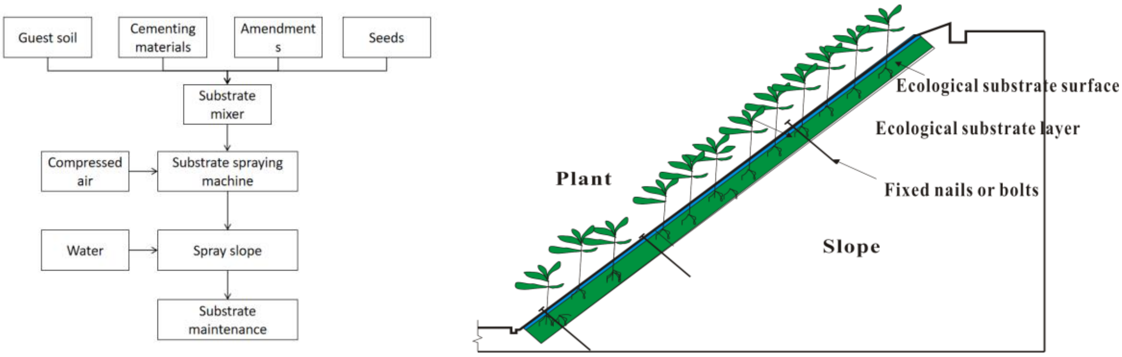
and shallow slope stability (Faiz et al., 2022; Xiao et al., 2017; Ma et al., 2019) (*Fig. 1*). This technology is widely applied to all kinds of geotechnical slopes such as highways, railways, mines, and rivers. The ecological substrate is the key to the successful implementation of external-soil spray seeding technology. The components of ecological substrate are use primarily consists of planting soil, cement, organic materials and ecological improvers (Kong et al., 2022). The ecological substrate should have the characteristics of strong resistance to rain erosion under long-term climatic conditions and high fertility suitable for long-term growth.




(a) (b)

***Figure 1.** External-soil spray seeding technology. (a) Technique flow chart; (b) conceptual model of vegetation slope protection*

The researchers have conducted in-depth theoretical and experimental research in the past ten years, which achieved breakthrough results and considerable social benefits. However, the research on the stability of external-soil spray seeding technology, such as ecological substrate stability, plant ecosystem stability, root mechanical properties and vegetated hydrological characteristics, is surely lagging behind and lacking (*Fig. 2*). The research results are limited, which leads to the unsatisfactory ecological slope protection effect and affects the further application of external-soil spray seeding technology. Based on the detailed study of the ecological protection slope stability with external-soil spray seeding technology, the objective of this article is therefore to summarize the stability of ecological substrate, vegetated ecosystem, the mechanical properties, hydrological characteristics of the external-soil spray seeding technology, and put forward the development direction of future research aiming, which provides a useful guideline for the project.

## Ecological substrate effect

To reach the physical and chemical properties required for plant growth, the ecological substrate must have sufficient stability. In other words, the substrate must have a certain adhesion and strength to be laid smoothly for the steeper rock slope. Chang (2022) designed a field test to study the effect of external-soil spray seeding greening additive on mechanical properties. Huang (2022) designed a large-scale shaking table test to study the failure mechanism of ecological substrates under different seismic excitation and different peak values Based on the Green-Ampt model and the mass conservation, Zhang (2021) derived the formula for calculating the allowable displacement of the ecological base layer under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rainfall. Qian (2022) studied the impacts of various fly ash and silica fume contents on the substrate mechanical properties. Ma (2019) studied the average conductivity and heating of an ecological substrate.

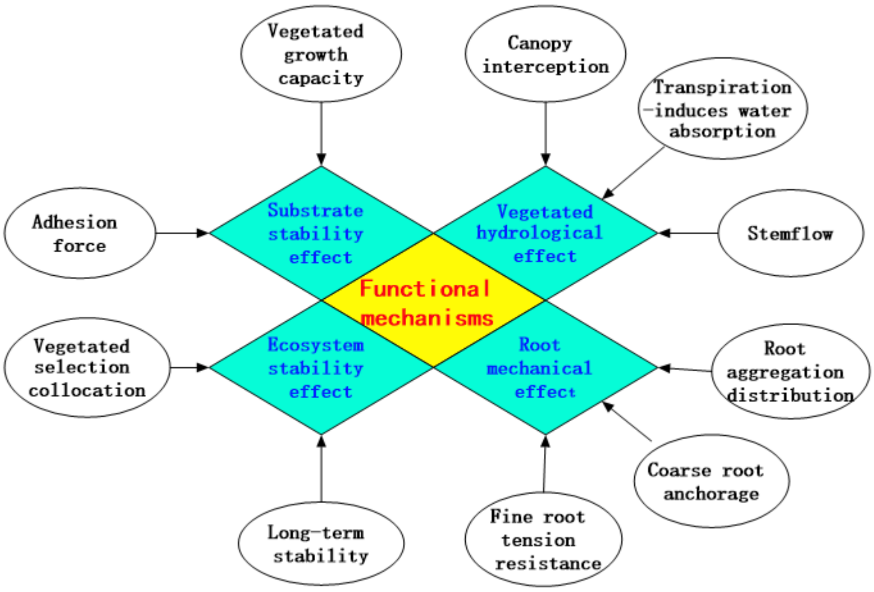


***Figure 2.*** *Functional mechanisms of external-soil spray seeding technology on slope stability*

Liu (2020) obtained the water holding capacity and erosion resistance characteristics of ecological substrate with different proportions through evaporation test, capillary test, and erosion test. Xu (2014) studied the stability of ecological substrate slope of railway ecological slope under earthquake and rainfall conditions based on the infinite slope model and Mohr-Coulomb strength criterion. Li (2014), Wan (2019), Ding (2014), Xiao (2015), and Yang (2015) studied the substrate unconfined compressive strength with different proportions in different periods. Wang (2017) designed the bearing capacity of chemical planting reinforcement for the connection of new anchors with low strength ecological substrates, which proposed the anchorage structure of small diameter reinforcing reinforcement coupled with grouting material. Ding (2016) conducted in-situ shear tests to study the shear characteristics of soil-rock interface for ecological substrates. Yu (2021) studied the effectiveness of polyurethane organic polymer on improving the substrate stability, and carried out strength experiment, scouring experiment and field experiment. Tang (2018) explored the effect of various fly ash contents on strength characteristics. Zhang (2017) studied the influence of slope site conditions, climate change and guest soil properties on the early substrate stability.

It can be known that amount of research has been done on the unconfined compressive strength of dry substrates, shear strength of substrates, and bond strength to rocks, etc. However, there are very few research results on the shear strength and bond strength under water saturation, which is a lack of in-depth research on the substrate stability theoretically. These are the key issues that determine the ecological substrate stability.


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**Research ecosystem stability effect**

The slope ecosystem established by external-soil spray seeding technology should rely on the functions of system self-support, system self-organization, system self-repair to complete the ecological communities succession, maintain long-term ecological stability, and achieve the purpose of slope permanent protection. So how should plant populations be properly allocated, can the slope site conditions reach the plant growth conditions, what are the effects on plant growth, can the established ecosystem maintain healthy and stable development under the slope site condition depending on its own conditions. To solve these problems, scholars have carried out some experimental studies.

Li (2022, 2021), Wang (2021), and Yu (2021) have specially studied the *Vetiver* (*Vetiveria zizanioides (L.)*) root distribution characteristics and slope protection effect. Chen (2021) studied the configuration of green plants in subtropical regions, and conducted some slope greening experiments. It is found that the *Bahiagrass* (*Paspalum notatum Fluegge*) is a good pioneer greening plant for ecological slope protection, which has strong scour resistance, adaptability, and stress resistance. Song (2021), Liang (2018), and Ji (2016) studied the adaptability of *Cynodon dactylon* (*Cynodon dactylon (L). Pers.*) to different climates and the influence of different substrate materials on the growth of *Cynodon dactylon*. They believed that *Cynodon dactylon* was a perfect slope protection plant, which can grow normally in the harsh environment where other grass species were difficult to survive. Mohammed (2018) found that *Cynodon dactylon* and *Vetiver* were bioengineering method to stabilize the slope soil against erosion investigating highway embankment. Luo (2024) constructed an ecological model slope covered with grass and shrubs, and analyzed the spatial variability and correlation of soil moisture in the ecological slope. Gao (2023) studied the protective effect of three mixed sowing combinations on roadside slopes of Shanxi expressway. Xia (2022) and Qin (2022) studied the slope ecological protection project in detail and the screening of vegetation according to different site conditions. Wang (2020) analyzed the optimal allocation mode of plant community of slope ecological restoration by selecting 15 plants and designed 10 plant community combinations. Zhou (2008) conducted field planting tests on 8 kinds of legume plants and concluded that these plants (*White triloba (Crustacea-Anomura)*, *Microcorolla variegata (Metamorphus corollae (F.))*, *Amorpha fruticosa (Amorpha fruticosa L.)*, *Lespedeza bicolor (Lespedeza bicolor Turcz)*, *Cronilla varia (Acrocomia Mart.)*, *Paspalum notatum (Paspalum notatum Flüggé)*, *Kummerowia striata (Kummerowia striata (Thunb.) Schindl.)*, and *Finches (Darwin's finches)*) could be the first choice of pioneer plant species for ecological restoration of stony slopes in Zhejiang Province. Chen (2017) conducted an experimental study on the rock-slope ecological stability by grass irrigation with different planting methods and accumulated some experience. Niu (2019) conducted field experiments on the selection of plant species and the mix ratio and obtained the vegetation species in expressways of alpine regions. Yamada (2024) monitored the vegetation on steep slopes of the Susogari grassland for three years and conducted a quantitative study on vegetation restoration. Liu (2009) adopted seven plants including Robinia pseudoacust (Robinia pseudoacacia L.) for slope protection and analyzed the growth index (height, growth rate, and coverage) relying on the slope of Chongqing Ring-cheng Expressway. Chang (2009) adopted external-soil spray seeding technology on the slope of 1:1.75 to carry out the mixed sowing experiment of 7 plants (including *Amorpha fruticosa*, *Cynodon dactylon*, and *Tall festilla ((Tarenaya hassleriana (Chodat) Iltis)*) and analyzed the growth index of different plant communities


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(coverage, aboveground biomass and shrub growth rate). Tamura (2017) measured native seedling density following germination of external-soil spray seeding technology to carry out the effectiveness of seed sowing techniques. Zhu (2009) studied the influence of different cement ratio matrixs on the seedling emergence rate and seedling height of four kinds of grass through experiments. The results showed that the appropriate proportion of cement components had little effect on the seedling emergence rate of grass seeds. With the increase of cement content in the matrix, the seedling emergence rate of grass seeds gradually decreased and affected the seedling height growth.

According to the current research status, the results mainly focus on the introduction, domestication, and allocation of grass species, which is only paid attention to short-term effects. There are few researches on the excellent original slope protection plants. For the slope site conditions built by external-soil spray seeding technology, there are fewer studies on the growth of original ecological plants. Although it has been applied in some projects, the research on the continuous follow-up of plant growth in the later periods is almost blank. At the same time, there is a lack of research on the effects of grass irrigation ratio, slope, seeding amount, and sowing season on long-term growth. These are the most important factors directly related to the planting ecological effect of slope.

## Root mechanical effect

### *Root mechanical properties*

Researchers from different countries have conducted in-depth studies on the reinforcement effect of plant roots, mainly using drawing test, in-situ shear tests, root tensile tests, and numerical simulation. Moreover, many research results have been achieved (Chen et al., 2016). Green (1911) believed that sagging taproots extend to the slope of the sliding shallow layers under ideal conditions. Waldron (1977) proposed a root-soil mathematical calculation model. Ferraiolo (1999) outlined the stabilizing effects of vegetation on slopes, including hydraulics and mechanical mechanisms. Woody roots reinforce the soil to form a tight layer through lateral roots, fibrous roots, and windings. Vertical roots of the anchor slope increase the sliding resistance. Roots increase soil shear resistance under stress changes through network action. Wu (1999) summarized the root action into simple shear model, chain linear model and elastic-plastic action model. Restenbery used sugar maple (*Acer saccharum*) with more branches for the root pulling test, and the experimental results showed that the maximum load was at a depth of 10 cm, which was much shallower than the theoretical calculation. White ash (*Frainus americana*), a taproot type with a few branches, was calculated to break suddenly at 3 cm, which is very close to the result. Zhu (2023) conducted the experiment on several species of plants with taproots, and the whole root was pulled out, which was consistent with Wu's research results. Gan (2023) believed that the roots would increase the soil shear strength with an increase rate of 5%-25%. Cheng (2020) measured that the compressive strength and porosity of porous concrete containing high fescue were at least 13 Mpa and increased by 21% after 28 days, respectively. Yang (2022) found that the cohesion of modified substrates shows an approximately linear increase trend with the increase of carboxymethyl cellulose sodium content.

Gao (2023) artificially mixed roots with soil and conducted direct shear tests on the reinforced soil of the *Vetiver* to study the root reinforcement effect. Preti (2010) can be used to evaluate the relationship between root zone and root strength by establishing the vegetated hydrogeological model. Yan (2010) tested the jointed grass with a diameter of


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0.6 mm and obtained that the tensile strength of the grass roots reached 22.32 MPa, which was 1/10 tensile strength of Grade I reinforcement. Lin (2024) conducted tensile tests on typical trees, and the results showed that the cohesion and friction coefficient of the root soil interface increased with the increase of root diameter, but the growth rate remained at around 15%. The cohesion decreases linearly with the increase of soil moisture content within the range of 25%-45%. Feng (2013) tested and measured the stress-strain relationship curve. The test showed that the root greatly improved the shallow slope ($H \leq 1$ m) stability and the root reinforcement gradually weakens for depths greater than 1 m. The improvement of soil shear strength completely depends on the average root tensile strength and the root zone. Through the drawing test, Feng (2013) obtained that the average tensile strength of vetiver roots was 85 MPa, equivalent to 1/6 tensile strength of ordinary steel. The relationship between the diameter of *Vetiver* roots and the tensile strength met the power function relationship. The study of Li (2014) showed that the stress-strain relationship was a logarithmic function and the strain increased rapidly, which was not in line with Hooke's law. However, *Miscanthus longmiscanthus*, *Cynodon dactylon*, *Branchia mongolica*, and *Artemisopsis mongolica* followed Hooke's law. Fu (2024) explored the mechanical properties of root systems and their influencing factors, and identifies the impact of standard length and root number on the tensile properties of root systems. Wang (2009) studied the root tensile performance of *Lustila fruticosa*, *Alfalfa (Medicago sativa)*, and *Koelreuteria koelreuteria (Koelreuteria paniculata Laxmann)* in Yogi Mountain slope in central China through experiments. The ultimate tensile strength, maximum tensile strength and roots elongation of four plants under different root diameter were discussed.

At the same time, the root water content varies with the change of climate or season. Root Water content affects the tensile strength (Rong et al., 2016). Studies have shown that the root strength of *Allotrope* (*Rothecamyricoides (Hochst.) Steane et Mabb*) is negatively correlated with root water content (Yuan et al., 2016). The dry root strength is greater than wet-root strength, but the dry-root diameter is smaller than that of wet root diameter (Hales et al., 2017). For shallow unsaturated soils, the change of root water content affects the root suction size and thus affects the ability of roots to absorb water (Tardieu et al., 2017). According to the above studies, root water content and root suction affect root mechanical properties, thus affecting root soil fixation (Boldrin et al., 2017).

In summary of the above research results, it is found that the root tensile strength is relatively large, which can reach 1/10~1/6 strength of ordinary steel bars. The mechanical properties of different plant root materials are different, so it is necessary to explore the root mechanical properties from the aspects of plant species and combined with the root site conditions.

### *Root-soil interaction*

Many scholars have studied the mechanical mechanism of root-soil fixation through field and laboratory tests in terms of root-soil interaction. Zhang (2023) explored pull-out tests at different angles under different root diameters to determine the optimal root soil mechanical interactions for coarse/fine roots and inclined/upright roots. Xu (2021) studied in detail the mechanical mechanism of root-soil fixation through laboratory tests and finite element simulation based on the assumption of root distribution. Zhao (2008) selected four representatively herbaceous for field shear measurement and quantitatively studied the improvement of the root-soil shear strength. Ma (2021) conducted a triaxial test of disturbed soil by dry–wet cyclic numbers and composite roots with different root


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content, to study the strength of the root-soil composites. Peng (2007) studied the stability of herbaceous slope under the combined hydrological and mechanical effects with a numerical simulation method. Yan (2010) quantitatively calculated the increased root shear strength and the increased slope stability coefficient by assuming the root number and root shape. Huang (2010) planted a single herb on external-soil spray seeding on the flat ground and compared the shear strength at different depths. They found that the herb roots significantly increased the cohesion.

Li (2007) studied the spatial distribution of herb-shrub roots on slopes in cold and dry areas. By establishing a mechanical model of root-soil interaction, they concluded that the root-soil mechanical effect was related to the root geometry and strength. Zhang (2008) used the finite element method to compare the shear stress of herb slope and no-herb slope for root-soil contact surface, which was used an elastic model, Duncan-Zhang nonlinear elastic model and hyperbolic model. Jiang (2008) conducted a direct shear test using 7-month-old dog teeth that were sun-dried and mixed with patterns according to a certain number and angle. The results showed that roots could significantly improve the soil shear strength, and it increased with the increasing in roots numbers. Shan (2008) found that the root-soil shear strength is shared by the complex of root-soil and roots. The roots cannot prolong the failure time of soil structure, but can only prolong the failure process of the complex of root-soil. Tang (2009) adopted three models (shallow root reinforcement model, deep root anchorage model, and root-soil combined reinforcement model) to analyze the influence of herb-bamboo roots on the stability of tunnel arch construction through three-dimensional numerical simulation. Liu (2024) addressed the insufficient numerical simulation of root soil interaction and explored the consideration of strain hardening/softening and shear dilation phenomena, deriving and implementing an improved Mohr Coulomb constitutive model. Hu (2010) carried out direct shear tests on disturbed soil samples with different root weights. The results showed that the roots could significantly increase the soil shear strength by 3.9%~21.2%, and some even reached 70%. The soil shear strength does not always increase with the increase of the root content. When the root content reaches a certain value, the soil strength does not increase.

Studies have found that the root retention capacity is related to the root distribution characteristics (Feng et al., 2013). Different root distribution characteristics have different influences on root-soil fixation strength and slope stability. Roots growing parallel to the slope reinforce the soil by increasing the root ensile strength, while roots extending perpendicular to the slope reinforce the soil by increasing the strength of the shear plane (Reubens et al., 2007). Herb root distribution can significantly increase soil shear strength in 0-20 cm soil layer (Zhao et al., 2008). The shrub root density decreased with the increase of soil depth. The root length density and root weight density in 0-60 cm soil layer accounted for more than 70% of the total root density. These results indicated that the soil root consolidation depends largely on root distribution (depth and spatial density). If the depth is not enough or the spatial density is not high enough, the coarse roots will be completely pulled out under the stress action and cannot reach the expected tensile strength, which has no significant contribution to the slope stability (Vergani et al., 2016). To describe the root distribution characteristics, researchers used parameters such as RLD (root length density), RWD (root weight density), and RAR (root area ratio) (Jin et al., 2019). The influence of root distribution varies with the plants growth time. The roots tensile strength and the root-soil shear strength change with the increase of root diameter, while the roots anchoring depth increases with the roots growth (Xia et al., 2013).


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As can be seen from the above research, a concentrated study has been carried out on herb root reinforced soil. The main study is to place a certain herb roots number or weight after sample preparation and conduct ordinary triaxial or conventional direct shear tests, to study the root reinforcement effect and the root-root mechanical properties. The numerical simulation was also based on the assumption of root morphological distribution. All these studies have simplified the root morphology distribution, ignored the roots-soil contact characteristics, and failed to accurately calculate the root mechanical action. It is difficult to accurately describe root-soil interaction mechanism. Almost all studies focus on the disturbed soil shear test of artificially added herb roots (dry roots) in soil and the numerical simulation of the assumed root shape distribution. Few of the corresponding indoor and field tests can be conducted on the basis of analyzing the actual roots distribution. To quantitatively analyze the root reinforcement effect, the root-morphology spatial and temporal distribution firstly must be made clear. In recent years, the study on the root distribution and dynamic growth has become a hot spot in ecological research (Wang, 2006). However, the research results cannot be completely copied to ecological slope protection, because the former research object is generally the forest roots in a natural state, while the latter is the herb irrigation roots greatly influenced by human. At the same time, there is a lack of research on the herb irrigation root morphological distribution under actual site conditions, and the influence of slope site conditions on root morphological distribution after spraying and planting is not taken into account. Various laboratory tests and quantitative analysis on the soil reinforced by herb-irrigation complex roots are few. The mechanical properties and reinforcing mechanism of herb-irrigation complex roots have not been truly revealed. In fact, the rock-slope properties, the ecological substrate properties and thickness, and the plant ratio have important effects on the root morphological distribution and other growth states. Therefore, the research results at the present stage can only serve as a qualitative reference at most because the assumed root morphology distributions are inconsistent with the actual situation. It is difficult to achieve the purpose of quantitative analysis.

## Vegetation hydrological effect

In terms of the plant hydraulic effect, many scholars have studied the plant hydraulic effect through field tests and numerical methods. Due to the difficulty in comprehensively considering the hydrologic effects on slope stability, the hydrologic effects of vegetation-soil-atmosphere are rarely considered (*Fig. 3*) (Stokes et al., 2014). Hydrological effects are attributed to plant transpiration, which is controlled by the exchange of water between the atmosphere, vegetation, and soil (Six, 2011). Plant transpiration can absorb soil water and produce suction in the soil, thus changing the engineering properties of soil. Wan (2017) conducted an experimental study on water evaporation of vegetation ecological substrates. Lu (2018) analyzed soil moisture under four planting cover types to reveal the hydrological effect mechanism of different vegetation cover types. Jesuslvarez (2014) carried out a series of studies on the impact of geotextiles in border protection and evaluated its runoff reduction and soil loss. The study found that geotextiles had great significance for the establishment of vegetation slope protection and vegetation growth. Yan (2015) and Gadi (2016) conducted a series of experiments and theories on soil moisture covered by vegetation on the slope surface.


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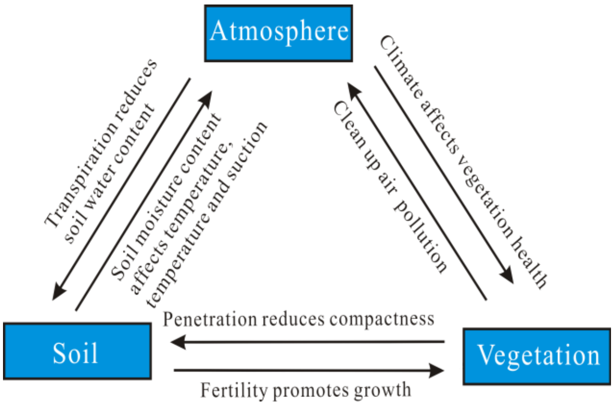


***Figure 3.*** *The relationship between vegetation-soil-atmosphere*

Soil erosion poses a serious threat to the integrity of the global ecosystem. Rain-induced landslide is considered particularly to be the main form of soil erosion and has caused a large number of casualty property losses (Schwilch et al., 2016 and Evette et al., 2012). Rain-induced landslide is generally considered caused by the reduction of soil shear strength in a certain slope depth under rainfall, which is related to many factors, such as vegetation, rainfall intensity, rainfall duration, rainfall pattern, slope topography and permeability, etc. (Weng et al., 2018). Relevant data of plant hydraulic power can help to make the selection of plants effective and sustainable. It can more effectively prevent and control the landslides possibility (Duan et al., 2016). The intensification of the water cycle due to global climate change is expected to increase the landslides frequency and severity (Gariano et al., 2016). The relevant data of plant water power can contribute to the plant sustainability of selection and more effectiveness preventing the landslide occurrence possibility (Yue et al., 2015). Dou (2018) studied the effect of plant root growth morphology on the shallow slope stability through numerical simulation. Plants can not only enhance the stability of the shallow slope through soil fixation by roots, but also absorb water in slope soil through hydraulic interception transpiration. Plant increases the soil suction and reduces the permeability coefficient, thus effectively reducing the infiltration amount of rainfall and enhancing the shear strength. Gariano (2016) established a stability threshold model of vegetation slope to study the influence of rainfall infiltration on vegetation slope threshold. Gonzalez-ollauri (2017) studied the flow-producing characteristics of vegetation blanket slope protection technology under different rainfall intensification conditions by artificial simulated rainfall test. It is believed that vegetation blanket had the most significant effect on reducing runoff and increasing infiltration. Chen (2016) conducted a simulated rainfall experiment to study the characteristics of soil displacement and soil pressure in cold areas and concluded that the *Caragana korshinskii* (*Caragana korshinskii Kom.*) roots could effectively inhibit soil deformation to a certain extent. Zhang (2013) studied the influence of soil macropores on rainfall infiltration in the unsaturated zones of a vegetated slope, and concluded that pore flow was generated by storm runoff. The acceleration of rainfall infiltration was mainly due to the increase of infiltration area. Liu (2018) derived the analytical solution of pore water pressure distribution in roots multilayer, and studied the influence of rainfall on permeability coefficient and pore water pressure. Wang (2006) used CT (Computed Tomography) scanning test and digital image processing technology to study the seepage characteristics in large soil. The results showed that rainwater formed preferential flow in


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longitudinally connected large pore channels, and the flow velocity in the channels was far higher than that in other parts.

From the current research status of the hydraulic effect of plant roots, the above research has carried out a certain study on the hydraulic characteristics of herb roots. The main research is to place the root layer of herb roots in different types of monitoring equipment, conduct on-site hydraulic parameter monitoring tests, and then study the changes in the root hydraulic performance. The numerical simulation was also based on the assumption of root morphological distribution. All these studies have simplified the root forms distribution, ignored the roots-soil contact characteristic and failed to accurately calculate the root hydraulic action. It is difficult to accurately describe the root-soil interaction and the mechanism of root water absorption. At the same time, there is a lack of research on the root morphological distribution of grass irrigation under actual site conditions, and the influence of slope site conditions on root morphological distribution after spraying and planting is not taken into account. There is little quantitative analysis of the hydraulic parameters of herb-irrigation complex roots. The hydraulic characteristics and reinforcement mechanism of herb-irrigation complex roots have not been truly revealed (*Fig. 4*).

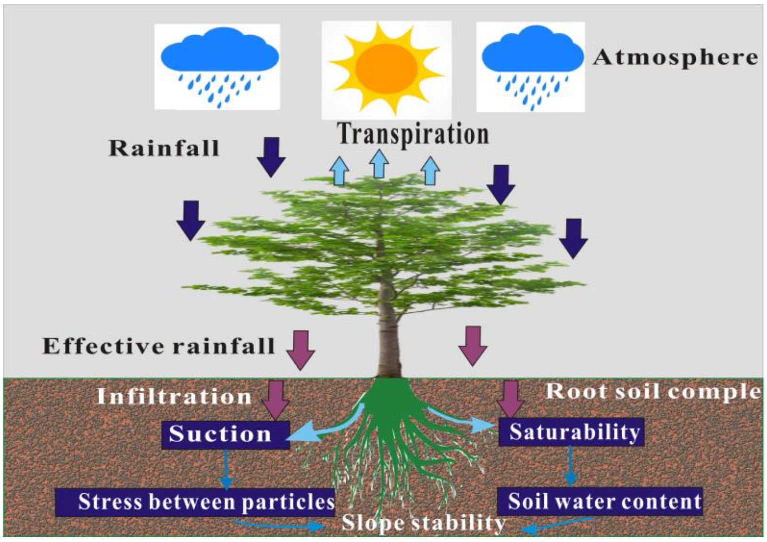


***Figure 4.*** *Conceptual model of vegetation slope protection*

## Conclusion and prospect

After more than ten years of development, the external-soil spray seeding technology has made great progress, and the ecological slope protection has achieved remarkable results. From the single use of grass seed plane slope protection to the combination of herb-irrigation and three-dimensional slope protection, from only paying attention to landscape effect to ecological coordination, from only paying attention to short-term effects to long-term effects. However, it is undeniable that the ecological slope protection level of external-soil spray seeding technology is still not high, and the slope protection effect is not ideal. There are many problems in short-term and long-term stability that need to be solved urgently, and the solution of these problems depends on the mechanical characteristics of external-soil spray seeding technology and the research breakthrough of plant ecological stability. Therefore, it is urgent and important to further strengthen the


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research on the slope stability with three-dimensional original ecological external-soil spray seeding technology.

From the history of the emergence and development of ecological slope protection, it is not difficult to see that external-soil spray seeding technology is the most important factor to promote the development of ecological slope protection. According to the research status of external-soil spray seeding technology, the research of substrate external-soil spray seeding technology presents the following development trends:

(1) Further studies will be made on the stability of the substrate shear strength and the bond strength of the rock, especially the shear strength and bond strength under water saturation.

(2) The development of slope ecological stability will be more rapid. Under the guidance of new ideas, such as emphasizing natural ecology and environmental protection in the new era, the ecological landscape construction of excellent original slope protection plants and external-soil spray seeding technology is more important. Therefore, more attention will be paid to the studies on the growth of original plants, the continuous tracking of the plants later growth, and the effects of herb-irrigation ratio, slope, seeding amount, and sowing season on long-term growth.

(3) The research results of root-soil interaction mechanism will be more abundant. The root- soil mechanical action is the most important factor to ensure the slope stability, and the quantitative root- soil research has become an important aspect of scientific research.

(4) Research on plant hydrological effects will develop more rapidly. The plant hydraulic mechanism is the most important factor to ensure the slope stability. It has become an important aspect of scientific research to strengthen the quantitative research on the root-soil hydraulic power.

In this paper, the present situation and deficiency of the theoretical research of ecological slope protection are fully discussed and the correct direction is provided for the future research. With the deepening of scientific research and technology, the theories and technologies of ecological slope protection will become increasingly perfect and mature.

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