Research on Vegetation Carbon Sequestration Enhancement Techniques for Highway in Hubei Province: A Case Study of the Shuangliu Bridge and Wiring Project

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Abstract. Highway greening can not only effectively improve the carbon sequestration capacity but also help to achieve the "carbon peaking and carbon neutrality" goals of the highway transportation industry. In this context, this paper screens plant species with significant carbon sequestration capacity suitable for highways in Hubei Province in combination with relevant classification standards. Furthermore, this paper develops the design patterns of high-carbon-sequestration plant communities for distinct vegetation zones, which are applied to the optimization of greening schemes in the interchange area of Shuangliu Bridge and its wiring project in Hubei Province. Under the premise of ensuring the landscape greening visual appeal, the design mode proposed in this paper improves the carbon sequestration capacity of the project, providing valuable enlightenment for the construction of low-carbon service areas and green highways.

Keywords: highway, vegetation, carbon sequestration, enhancement

1 Introduction

Following China's"carbon peaking and carbon neutrality" goals in 2020, reducing emissions and increasing carbon sequestration emerge as key tasks of contemporary economic and social development. Hence, it is of paramount urgency to realize the high-quality development of the highway transportation sector, the main body of carbon emissions. In recent years, Hubei Province has vigorously promoted the development of green recycling and low-carbon transportation, integrating the construction of ecological civilization into all aspects of the transportation process. For instance, the Department of Transport of Hubei Province issued diverse official documents, such as the *Low-Carbon Transportation Construction Action Plan for Wuhan Metropolitan Area (2013-2018)* and the *Green Low-Carbon Transportation Action Plan for the Ecological Cultural Tourism Circle of Western Hubei (2013-2018)*.

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To facilitate the realization of the "carbon peaking and carbon neutrality" goals, it is necessary to adopt negative emission technology besides significantly reducing fossil fuel emissions [1]. At this point, the comprehensive framework based on emission inventory, tree species, morphology, and ecosystem modeling proposed by Brilli et al. [2] shows that effective vegetation management can significantly improve the CO_2 sequestration capacity of cities under the actual conditions and the afforestation scenario of maximizing CO_2 sequestration capacity. According to the research of Peng Yuting [3], the green area of the Zhejiang highway service area, with an influence coefficient greater than 0.7, significantly impacts low-carbon operations in service areas. Zhang [4] proposed new low-carbon construction and maintenance techniques applicable to highway greening, while Shi et al.[5] measured the carbon sequestration and oxygen release capacity of various garden plants in Wuhan, indicating that the carbon sequestration capacity of evergreen plants was greater than that of deciduous plants. By measuring the photosynthetic rate of 151 plant species in Shanghai, Wang et al. [6] investigated their carbon sequestration and oxygen release capacity. Furthermore, Liu [7] performed research on carbon sequestration, oxygen release, cooling, and humidification of evergreen plants along southern highways. Based on the theory of carbon sequestration, Zhou et al.[8] screened and configured the landscape greening plants of Guizhou highways, constructing a carbon-sequestering ecosystem that meets functional, aesthetic, and environmental standards. Based on these findings, this paper implements the research related to vegetation carbon sequestration enhancement techniques for highway in Hubei Province, which has been applied to the Shuangliu Bridge and its wiring project in Hubei Province.

2 Carbon Sequestration Enhancement Techniques for Plants

2.1 Carbon Sequestration Capacity of Individual Plants

The carbon sequestration of plants is defined as a process, activity, or mechanism that uses plant photosynthesis to absorb carbon dioxide in the atmosphere and store it in vegetation and soil through afforestation, forest management, and vegetation restoration measures to reduce the concentration of greenhouse gases in the atmosphere [9]. By investigating the plant resources within two vegetation zones and five vegetation regions in Hubei [10], this paper selects 89 plant species with application frequencies above 10% as the research object based on the principle of highway greening application. Based on their carbon sequestration and oxygen release capacities, these plant species are divided into three levels: better, middle, and less. Meanwhile, following landscape greening classification principles, these plant species are classified into trees (such as backbone trees, colored-leaf trees, flowering/fruiting trees, etc.), tall shrubs, low shrubs, vines, herbs, etc., as shown in Table 1.

Table 1. The carbon fixation and oxygen production grade of a leaf area unit (in a day).

Grade	Better (CO_2 > 10 $g \cdot m^{-2} \cdot d^{-1}$, O_2 > 7.3$g \cdot m^{-2} \cdot d^{-1}$)	Middle (CO_2=6 ~ 10 $g \cdot m^{-2} \cdot d^{-1}$, O_2=4.4 ~ 7.3 $g \cdot m^{-2} \cdot d^{-1}$)	Less (CO_2 < 6 $g \cdot m^{-2} \cdot d^{-1}$, O_2 < 4.4 $g \cdot m^{-2} \cdot d^{-1}$)
No. A1 Backbone Tree -Evergreen Trees	*Magnolia grandiflora* *Cinnamomum camphora*	*Elaeocarpus sylvestris*	*Livistona chinensis* *Trachycarpusfortunei*
No. A2 Backbone Tree - Deciduous Trees	*Sophora japonica* *Aphananthe aspera* *Platanus acerifolia* *Salix babylonica* *Juglans mandshurica* *Paulowinia fortune* *Camptotheca acuminata* *Eucommiaceae*	*Pterocaryastenoptera* *Firmianaplatanifolia* *Aesculus chinensis* *Ailanthus altissima* *Robinia pseudoacacia* *Ulmus pumila*	*Catalpa ovata* *Celtis sinensis*
No. A3 Colored Leaf Tree - Deciduous Trees	*Sapiumsebiferum* *Pistacia chinensis* *Diospyros kaki*	*Ginkgo biloba* *Albizia julibrissin* *Koelreuteriapaniculata* *Acer buergerianum* *Sapindusmukorossi* *Liquidambaformosana* *Metasequoia glyptostroboides* *Liriodendron chinense* *P. cerasifera cv*	*Zelkova serrata*
No. A4 Flowering/Fruiting Tree-Small Tree	-	*Malus halliana* *Magnolia heptapeta* *Cornus officinalis* *Eriobotrya japonica* *Cercis chinesis* *Armeniacamume* *Michelia figo* *Nerium indicum*	*Osmanthus fragrans* *Ligustrum lucidum* *Photiniadavidsoni-aeRehd* *Prunus serrulata* *Crataegus pinnatifida* *Punicagranatum* *Lagerstroemia indica*
No. B1 Tall Shrubs	*Edgeworthiachrysantha* *Camellia japonica* *Hibiscus mutabilis*	*Acer Palamatum* *Hypericum monogynum* *Cerasus japonica* *Lonicera maackii*	*Sorbariasorbifolia* *Weigela coraeensis*
No. B2 Low Shrubs	*Buddlejalindleyana* *Rhododendron fortunei* *Hydrangea macrophylla*、 *Jasminum floridum* *Chaenomeles speciosa*	*Ligustrum quihoui* *Fatsia japonica* *Yucca gloriosa* *Forsythia viridissima* *Berberidaceae* *Buxus sinica*	*Pyracantha fortuneana* *Physocarpusamurensis* *Mahonia fortunei* *Aucuba japonica*

		Gardenia jasminoides *Ilex cornuta* *Spiraea japonica* *Indocalamustessellatus*	
No.C Vines	-	*Hedera nepalensis* *Campsis grandiflora* *Trachelospermum jasminoides* *Actinidia arguta*	*Vitis vinifera* *Vinca major*
No. D Herbs	*Festuca rubra*	*Farfugium japonicum* *Hemerocallis fulva* *Hosta plantaginea* *Caldesia* *Poapratensis*	-

2.2 Carbon Sequestration Capacity of Plant Community

Plant communities featuring high biodiversity, with their stable environment as well as remarkable self-regulation and resilience, show relatively robust carbon sequestration capacities [11]. Typical natural communities in Hubei Province are mainly composed of mixed evergreen and deciduous broad-leaved trees, which are generally characterized by three to five layers of mixed evergreen and deciduous broad-leaved trees as well as a multi-layer tree-shrub-grass structure. Effective performance of carbon sequestration and oxygen release of these plants benefits from protecting current plant communities, enhancing the site's habitat adaptability, and increasing species diversity, and second by prioritizing the retention of large trees for their superior carbon sequestration and minimal maintenance requirements. With regard to the same piece of highway green space, varying plant configurations potentially lead to significant differences in carbon sequestration, with a multi-layered tree-shrub-grass configuration achieving over three times the carbon sequestration of a grass-only configuration. Thus, the concrete construction of plant communities should emphasize the rational collocation of plant species and the flexible construction of spatial layering, intending to amplify ecological benefits beyond the sum of individual plant contributions.

Following the principle of constructing a "multi-layered, mixed, and uneven-aged" near-natural plant community, this study integrates various plant compositions, encompassing tree-shrub, tree-grass, shrub-grass, vines, herbs, etc. Through a balanced combination of evergreen and deciduous species, as well as fast-growing and slow-growing trees, age diversity within the tree population is maximized, thereby enhancing the efficiency of carbon sequestration of the plant community. On this basis, this research develops a total of four types of high-carbon-sequestration planting configuration patterns, as detailed in Figure 1.

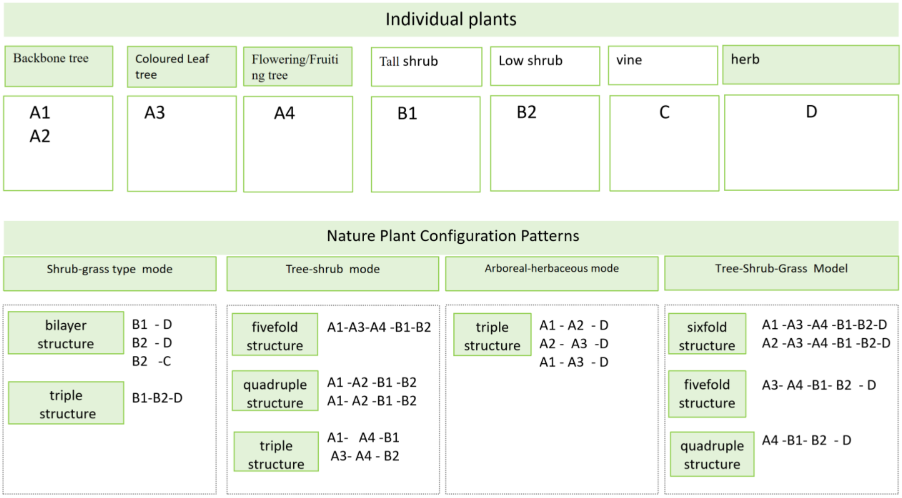

Fig. 1. Planting structure of near-natural plant community.

2.3 Plant Configuration Patterns of Highway Greening

Highway greening is mainly concentrated in a series of areas, such as interchange zones, building zones, subgrade slopes, central dividing zones, and tunnel entrance zones. Correspondingly, their plant configuration principles are summarized as follows.

1. Interchange zones: Interchange zones should prioritize the selection of plant species featuring deep root systems, minimal maintenance demands, and robust tolerance to extreme weather conditions, with dominant planting modes in these zones consisting of tree-shrub-grass, tree-shrub, and tree-grass structures.
2. Building zones: Adhering to principles of human-centered design, building zones should prioritize the selection of thematic and distinctive plant species suitable for large-scale, cohesive planting, with dominant planting modes in these zones consisting of tree-shrub-grass, tree-shrub, and tree-grass structures.
3. Subgrade slopes: Subgrade slopes should prioritize the selection of native herbaceous species with high carbon sequestration potential, while cutting slopes should prioritize the selection of vines such as *Hedera nepalensis* and *Campsis grandiflora*, thereby creating a natural green space. As such, the primary planting configuration in these zones should adopt the shrub-grass mode.
4. Central dividing zones: Central dividing zones should prioritize the selection of highly adaptive plant species with slow growth characteristics, which are resilient to nutrient-poor soils, extreme temperatures, wind, and sand exposure, to prevent foliage from infringing upon road clearance zones and affecting driving safety. Therefore, the primary planting configuration in these zones should adopt the shrub-grass mode.

5. Tunnel entrance zones: The front slope of tunnel entrances should be protected as much as possible to preserve the original vegetation around the slope. With an emphasis on ecological restoration, tunnel entrance zones should prioritize the rational combination of shrubs, vines, and herbs, thus realizing the perfect adaptation of vegetation communities to the surrounding environment. Consequently, the primary planting configuration in these zones should adopt the shrub-grass mode.

Based on the planting principles for each greening zone along highways, this research further identifies the most suitable near-natural plant community structures for them. Additionally, while recommending optimized configuration models for high-carbon-sequestration plants, this research estimates the net daily carbon sequestration per unit area of green space in each zone, as presented in Table 2.

Table 2. Configuration Patterns of High-carbon-sequestration Plants for Diverse Highway Greening Zones.

Greening zones	Planting structure of plant communities	Recommended configuration modes with specific vegetation coverage types	[a] Capture Total ($g \cdot m^{-2} \cdot d^{-1}$)
1 Interchange zones	Tree-shrub-grass model	Fivefold-sixfold structure: Backbone tree + colored leaf tree + flowering/fruiting tree + tall shrub layer + low shrub layer + herb/grass(70% trees coverage, 30% shrubs coverage, and 70 % herb/grass coverage)	65
2 Building zones	Tree-shrub-grass model	Quadruple structure: Backbone tree + tall shrub layer + low shrub layer + herb/grass (50% trees coverage, 50% shrubs coverage, and 50% herb/grass coverage)	58
3 Subgrade slopes	Shrub-grass type model	Triple structure: Tall shrub layer + low shrub layer + herb/grass (70 % shrub coverage, 30% herb/grass coverage)	36
4 Central dividing zones	Shrub-grass type model	Bilayer structure: Shrublets + herb/grass (80% shrub coverage, 20% herb coverage)	38
5 Tunnel entrance zones	Shrub-grass type model	Bilayer structure: Shrublet layer + vine layer (40% shrub coverage, 60% vine coverage)	28

[a] The net daily carbon sequestration rates per unit green area ($g \cdot m^{-2} \cdot d^{-1}$) for areas exclusively planted with a single vegetation type are as follows: 50.9 for trees, 41.9 for shrubs, 18.65 for vines, and 23.38 for herbs [12].

3 Case Validation

The plant species involved in the original greening scheme mainly include native and locally adaptive species, displaying high visual appeal. Nevertheless, certain plants inevitably expose such defects as reduced carbon sequestration capacity, a lack of planting diversity, and limited multi-layer planting structures, thereby restricting the overall potential for carbon sequestration.

To address the defects identified in the original scheme, this research optimizes the greening scheme of three interchanges of the Shuangliu Bridge and its wiring project in Hubei Province from the perspective of plant species selection and plant community planting structure configuration, intending to improve their total carbon sequestration capacity. Specifically, the optimization of plant species selection, on the one hand, aims to replace certain high-carbon-sequestration plant species on the premise of reducing seedling quantities and minimizing project costs. On the other hand, the optimization of plant community planting structure mainly emphasizes adjusting the single- and double-layer planting configurations to multi-layered ones.

1) Huarong Interchange

Prunus serrulata, in the original greening scheme for Huarong Interchange, presents limited carbon sequestration and a relatively single planting structure. Given this, regarding the further scheme optimization, it is suggested to replace *Prunus serrulata* with *Camellia japonica* and *Hibiscus mutabilis* while reducing trees such as *Cinnamomum camphora* and *Magnolia heptapeta* as well as increasing tall shrubs such as *Osmanthus fragrans* and *Camellia japonica*, thereby forming a multi-layered planting structure. Following optimization, a dual-layered planting structure was introduced to form the A1 (*Magnolia grandiflora/Cinnamomum camphora*)-A3 (*Sapindusmukorossi*)-A4 (*Magnolia Heptapeta/Osmanthus fragrans*)-B1 (*Camellia japonica/Hibiscus mutabilis*)-D (*Herb*) configuration mode when the total number of seedlings decreased by 128. In addition to prolonging flowering periods and improving carbon sequestration capacity, this configuration mode increases the net-daily carbon sequestration amount by 4,564 $g \cdot m^{-2} \cdot d^{-1}$, which is 43% higher than the original scheme, as shown in Figure 2.

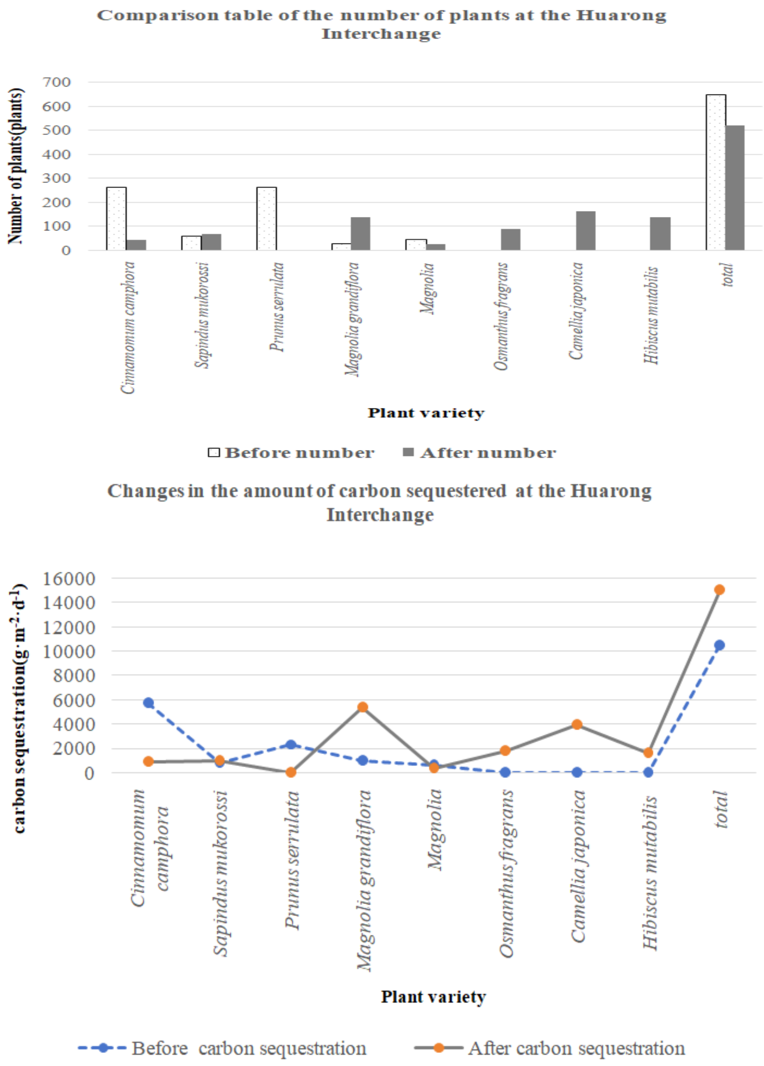

Fig. 2. Changes at the Huarong Interchange.

2) Zhucheng West Interchange

Optimization of the greening scheme for Zhucheng West Interchange involved reducing 119 trees, including *Cinnamomum camphora*, *Magnolia*, and *Prunus serrulata*, with the vacated area used to plant 520 low shrub *Buddlejaceae*. Through optimization, a monolayered planting structure was introduced to form the A1 (*Cinnamomum camphora*)-A4 (*Magnolia*)-B2 (*Buddlejaceae*)-D (*Herb*) configuration mode. This configuration mode increases the net daily carbon sequestration amount by 4,545 g·m^{-2}·d^{-1}, which is 98% higher than the original scheme, as shown in Figure 3.

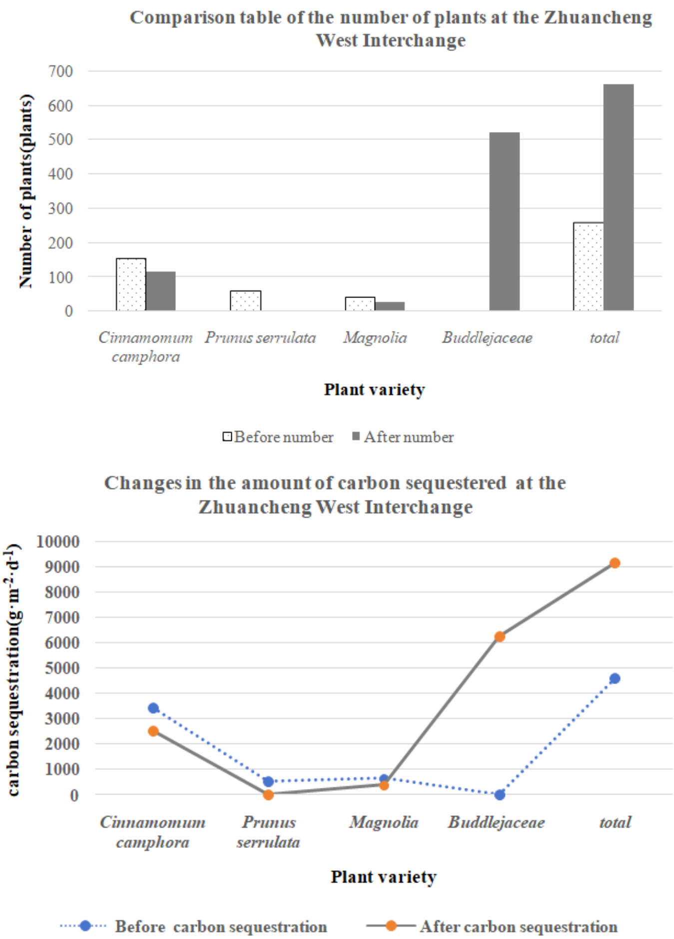

Fig. 3. Changes at the Zhucheng West Interchange.

3) Lianhufan Interchange

The original greening scheme for Lianhufan Interchange was characterized by a single-layer structure and the inclusion of *Nerium indicum*, a toxic species. With regard to further scheme optimization, it is suggested that 120 Nerium indicum plants be reduced, with the vacated area used for planting 65 *Sapiumsebiferum* plants and 55 *Acer Palamatum* plants. Through optimization, a monolayered planting structure was introduced to form the A3 (*Sapiumsebiferum*)-B1 (*Acer Palamatum*)-D (*Herb*) configuration mode. In the case that the total number of seedlings remains unchanged, this configuration mode highlights the landscape effect of colored leaves in autumn while improving the carbon sequestration capacity. Simultaneously, it increases the net daily carbon sequestration amount by 2,219 $g \cdot m^{-2} \cdot d^{-1}$, which is 75% higher than the original scheme, as witnessed in Figure 4.

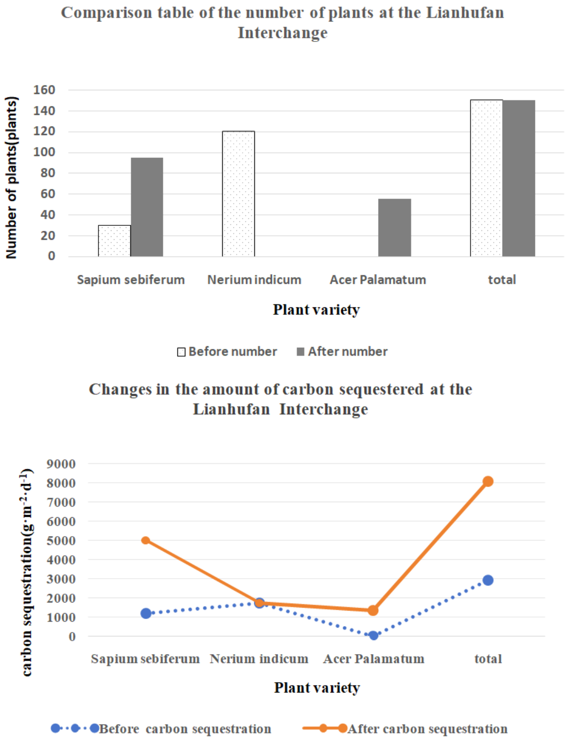

Fig. 4. Changes at the Lianhufan Interchange.

4 Conclusion

In summary, the findings of this research indicate that the carbon sequestration capacity of highway greening areas can be significantly improved by optimizing plant planting structures and selecting high-carbon-sequestration plant species that adapt to the local environment. During the practical application of highways in Hubei Province, the improvement of the greening scheme has successfully increased its total carbon sequestration capacity. These findings are significant for achieving the goals of carbon peaking and carbon neutrality, most importantly, providing a valuable reference for the future development of green and low-carbon transportation.

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