biomass nitrogen, and nodule number (Luo et al., 2024). Root interaction studies also showed that closer interspecific contact can intensify symbiotic nitrogen fixation, promote nitrogen assimilation and amino-acid export, and ultimately raise nitrogen-use efficiency and yield in intercropped pea. For Zhejiang, these results suggest that stable legume yields are more likely where species possess efficient nodulation, strong root plasticity, and compatibility with diversified cropping systems that improve belowground ecological function.

6.3 Genetic characteristics and genotype-environment interactions

The genetic basis of yield stability in legumes is inseparable from genotype-environment interaction, because the same genotype can perform very differently across locations, years, and management conditions. In faba bean, yield instability is explicitly attributed to GEI, and large interaction effects reduce heritability and weaken the correspondence between phenotypic performance and genetic value, making selection progress slower (Sokolović et al., 2025). Similar evidence from chickpea shows that stability breeding must distinguish between static stability, where performance changes little across environments, and dynamic stability, where genotypes respond predictably while maintaining high productivity (Eskezia et al., 2025). This implies that legume yield stability in Zhejiang should be interpreted not as simple invariance, but as the ability of a species or genotype to maintain relatively high yield under environmental fluctuation without excessive rank reversal.

A second mechanism is the presence of usable genetic diversity for adaptive traits, together with analytical tools that identify broadly or specifically adapted materials. Studies in faba bean show that stable variety development depends on substantial genetic variation, because this diversity provides the basis for selecting cultivars suited to local climate, altitude, and soil conditions. At the same time, crossover interactions can shift genotype rankings across yield environments, so identifying where these crossovers occur helps separate narrowly adapted from broadly adapted materials and avoids yield penalties from poor genotype choice. Breeding for stable legume production therefore requires combining diverse germplasm, multi-environment testing, and methods such as GGE, AMMI, or multi-trait stability indices to match genotypes to the ecological heterogeneity typical of Zhejiang. Overall, yield stability formation in legumes depends on three linked mechanisms: climate adaptation under compound stress, efficient physiological-ecological support for nitrogen and biomass production, and genetic adaptation shaped by genotype-environment interaction. These mechanisms jointly determine whether a legume species can sustain reliable yield across Zhejiang's diverse environments.

7 Case Study: Yield Stability Analysis of Legume Crops in Typical Ecological Regions of Zhejiang Province

7.1 Selection of study regions and research design

The case study regions should be selected to represent the main ecological contrasts that shape legume production in Zhejiang, such as plains, river-valley basins, coastal areas, and hilly uplands. Multi-environment trials are the standard design for evaluating adaptation and stability across heterogeneous conditions, because they allow the same crop materials to be compared under differing temperature, rainfall, soil, and management backgrounds. Experience from Chinese pea trials further shows that broad climatic coverage across locations and years is necessary for identifying both widely adapted and specifically adapted materials, rather than assuming that one genotype or species performs uniformly everywhere.

Accordingly, the research design for Zhejiang can be organized around several representative county-level sites, with each site-year combination treated as an independent environment and each legume species tested under a unified field protocol. Similar legume studies commonly use randomized complete block or lattice designs with three to four replications, which improves the precision of yield comparison under variable field conditions (Haile and Tesfaye, 2024). Case studies from other ecological regions also show that dividing production areas into mega-environments helps identify groups of locations with similar crop responses, making regional interpretation more meaningful than using provincial averages alone (Figure 3).

7.2 Yield stability performance

In the case study regions, the first expectation is that different legume crops will show clear differences in both mean yield and stability because genotype, environment, and their interaction usually all contribute significantly