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Geostatistical analysis of regional differences in stem taper form of *Pinus densiflora* in central Korea

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Abstract This study verified regional differences in the stem form of *Pinus densiflora* Sieb. et Zucc. (red pine) and identified the relationship between stem form and climatic factors in the central region of the Korean peninsula. Regional differences in stem form index at tree base (butt) and top stem section were found. Compared to the stem form in the eastern uplands, the stem form in the western lowlands could be characterized by a more conical butt section and more cylindrical middle and upper section. Through geostatistical analysis of kriging and spatial regression, several climatic factors proved to exert a meaningful influence on stem taper form. On the stem form at the butt section, the precipitation during the late growing season exerts statistically significant effects. High precipitation during the growing season in the western lowland and coastal region causes the stem form at the butt section to be more tapered. On the stem form at the middle and upper section, temperature and precipitation during the growing season, and wind during the late growing season have statistically meaningful influences. High temperature, precipitation, and wind during the growing season in the western lowland and coastal region jointly influence the stem form at the middle and upper sections which result in more cylindrical profiles. This study can be considered an initial investigation into the factors controlling stem form variability in the central region of

the Korean peninsula. The results can be used to develop more accurate regional stem taper models needed for reasonable management of red pine stands in different regions.

Keywords Stem form · Regional differences · Climatic factors · Geostatistical analysis · Kriging

Introduction

The topography of the central region of the Korean peninsula is characterized by gradually decreasing elevation from east to west (Fig. 1a). One of the biggest ridges of Taebaek stretches from north to south along the eastern coast. From this mountain ridge, the elevation decreases gradually westwards. The eastern upland is characterized by higher elevation and lower temperature in comparison to the western lowland with lower elevation and higher temperature. This different topography brings about differences in climate, and composition and growth of tree species.

Considered one of the most economically and culturally important tree species, *Pinus densiflora* Sieb. et Zucc. (red pine) has shown also regional differences in growth and stem form. Uyeki (1928) classified red pine into six regional ecotypes on the basis of stem and crown form, of which the Keumkang ecotype and the central southern lowland ecotype represent the tree form of red pine in central Korea.

The Keumkang ecotype, named *P. densiflora* for. *erecta* by Uyeki, is characterized by straight boles, tall tree heights, thin branches and conical-shaped crowns with a narrow crown width and long crown length (see Fig. 1b). This tree ecotype was reported by Uyeki to be distributed along the Taebaek ridge in the central eastern upland with a low temperature and humid climate. The central southern lowland ecotype, which represents the tree form in the low elevation and flatland areas of central western Korea with a high temperature and dry

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climate, is characterized by non-straight boles that sweep, short tree heights, parabolic-shaped crowns with wide crown width and short crown length. Uyeki also reported that the intermediate form between Keumkang and the central southern lowland ecotype, named the central southern upland ecotype, could appear in central Korea depending on topographic and climatic conditions.

It has been widely recognized that there are regional differences in growth and stem form of red pine regardless of silvicultural treatments. And central Korea has been traditionally delimited into a central western and a central eastern region for managing the red pine (see Fig. 1). So different volume (Kim 1965; Lee 1971b; Kim et al. 1994; Lee et al. 1999) and yield models (Kim 1963; Lee 1971a; Lee et al. 1993) have been prepared for these two regions and applied in forest practices. These different models and their application in forest practices were initiated by the well-known traditional understanding of variation in growth and stem form.

Relative stem profile equations (Inoue and Kurokawa 2001a) and volume equations (Inoue and Kurokawa 2001b) for coniferous species including *P. densiflora* were derived for application to a system yield table in Japan. And several stem form and taper models have been proposed in Japan (Nagashima et al. 1980; Sweda 1988; Nagashima and Kawata 1994). However, the regional differences in the stem form of red pine and the relationship between stem forms of red pine and climatic factors have not been reported.

Several attempts have been also made to genetically verify the geographic variation in growth and stem form of red pine (Kim and Lee 1992, 1993, 1995, 2005; Lee et al. 1997; Kim and Han 1997). However, the regional differences in stem form have not been verified through stem taper model and stem form indices, and no

attempts to explain the regional differences in stem form in relation to geographic and climatic factors have been made.

This study investigated the stem form of red pine in central Korea for the purpose of verifying the regional differences in stem form and identifying the relationship between stem form and climatic factors.

Materials and methods

Study area

Our study focuses on red pine ecotypes in central Korea. Data were collected in administration units (guns) (Fig. 1a). In this study there are a total of 39 guns of which 19 are located in the central eastern upland region of Kangwon and Kyoungbuk Province, and 20 in the central western lowland region of Kyounggi and Chungcheong Province.

Measurements

A total of 4,269 trees from 39 guns were measured and analyzed for regional variability of stem form (Table 1). We selected naturally regenerated homogeneous dense stands without silvicultural treatments for the last several decades, and measured dominant or co-dominant trees. DBH of the outside bark (cm), tree height (m), and diameters of the outside bark at different stem heights (cm) were used for deriving taper models and stem form indices. Mean monthly temperature, precipitation and wind speed of the guns for the last 5 years were available from the database of the Korean Meteorological Administration and used for comparing stem form and

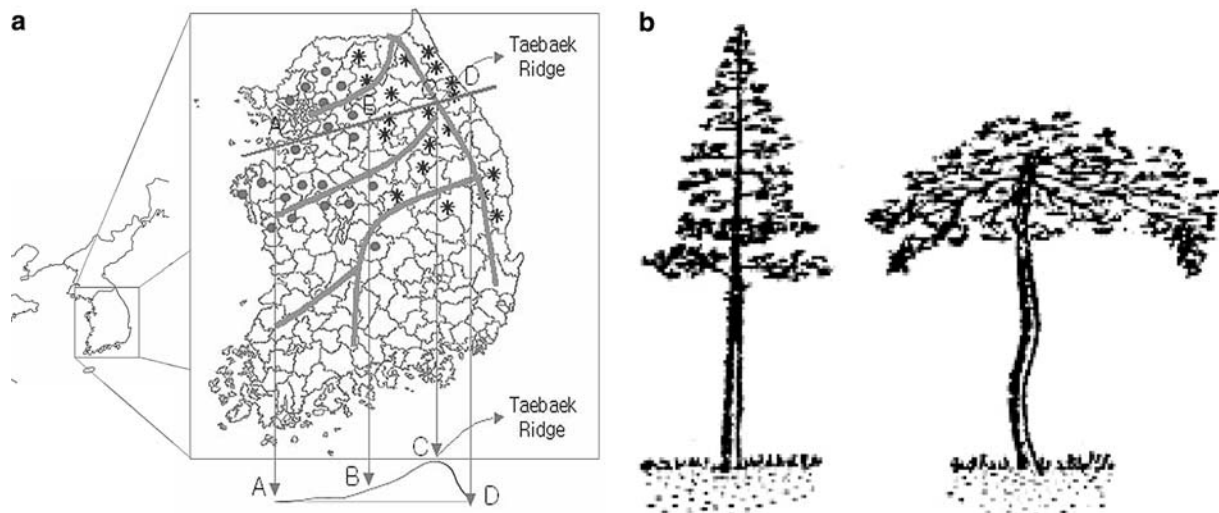


Fig. 1 a Diagram of the study area and administrative units (guns) where tree boles were measured. Circles indicate 20 guns in the central western region of Kyounggi and Chungcheong Province and asterisks indicate 19 guns in the central eastern region of

Kangwon and Kyoungbuk Province where tree boles were measured. b Uyeki's tree form of *Pinus densiflora* in Korea described by Lim (FRI 1999). Left Keumkang ecotype, right central southern lowland ecotype

Table 1 Description of the study regions and relevant data. *DBH* Diameter at breast height

Region	No. guns	No. trees	DBH (cm)		Height (m)		Elevation (m)		Temperature (°C/month)		Precipitation (mm/month)		Wind speed (m/s per month)	
			Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Central western	20	1,830	25	6–72	14	4–32	122	20–311	12	10–17	112	93–137	1.4	0.8–2.6
Central eastern	19	2,439	30	6–82	17	5–36	387	186–749	12	10–16	103	85–118	1.7	0.8–3.5
Total	39	4,269	38	6–82	16	4–36	251	20–749	12	10–17	108	85–137	1.5	0.8–3.5

climatic factors. For geostatistical analysis, the universal transverse mercator (UTM) coordinates of centroids of each gun-polygon were prepared using geographic information systems (GIS), and stem form indices and climatic factors were assigned to these UTM coordinates.

Stem taper model and stem form index

Lee's stem taper model with variable exponent (Lee et al. 2003) was applied for deriving various stem form indices.

$$d = k_1 DBH^{k_2} (1 - Z)^r,$$

$$r = f(Z) \quad (1)$$

$$= r_1 Z^2 + r_2 Z + r_3, \quad (k_1, k_2, r_1, r_3 > 0, r_2 < 0)$$

where DBH is diameter at breast height (1.2 m) outside bark (cm), d is observed stem diameter outside bark at height h , Z is relative height (h/H), h is height of the stem above the ground (m), and H total tree height (m).

Lee's model assumes that the exponent (r) continuously varies with height and can be expressed by a second-degree polynomial equation of relative height Z . This model has proven to be suitable for stratifying trees into different groups on the basis of stem form indices that can be derived from the variable- r of the model (Lee et al. 2003). Stem form is defined here as the geometrical shape of the stem profile between two stem heights, while stem taper is defined as the rate of decrease in diameter along the tree bole with increasing height (Gray 1956; Morris and Forslund 1992; Muhairwe 1999). The r of Lee's model can produce different stem profile such as neiloidal ($r = 1.5$), conic ($r = 1$), paraconic ($r = 0.75$), parabolic ($r = 0.5$), or cylindrical ($r = 0$). The r s at relative heights of 0.05 (r_{005}) and 0.9 (r_{09}), and stem form indices such as inflection point (IP)¹ and minimum (r_{min}) are used as proxies for representing the entire stem form in our study. The r_{005} and r_{09} represent the stem form at the butt and top section of the stem, respectively. The lower the values of r_{005} and r_{09} are, the less tapered (more cylindrical) are the butt and top sections of the stem. IP and r_{min} are the stem form indices for describing stem form of the middle section. A

lower IP and r_{min} correspond to a stem form that is less tapered (more cylindrical) in the middle or upper sections.

Cluster and geostatistical analysis

Cluster analysis was performed for stratifying trees into different form groups. Variogram analysis and kriging (Bailey and Gatrell 1995; Mowrer and Congalton 2000, Webster and Oliver 2001) were the geostatistical tools used to identify spatial autocorrelation and variability of stem form indices and climatic factors. Spatial multiple regressions with the dependent variable of stem form indices and independent variables of climatic factors were performed for analyzing the relationship between stem form indices and climatic factors. The CLUSTER procedure of SAS (SAS Institute 2000) was used for cluster analysis and S+SPATIAL STATS module of SPLUS (Kaluzny et al. 1998) was used for geostatistical analysis.

Results and discussion

Grouping of the stem forms by cluster analysis

r for different regions

Figure 2a, b shows the predicted r of taper models for different regions and the mean r with SD. The high value of r at the butt (base) section decreases with increasing stem height, reaches the minimum value and slightly increases again. This pattern of r properly represents the usual stem form that is conical or neiloidal at the butt section and becomes more parabolic with increasing stem height. There are differences in the pattern and SD along the stem height and in values of r at specific stem heights.

The differences at the butt and top section are more distinctive than that at mid section. This implies that there is a relatively low regional difference for the middle section of trees while the stem form at the butt and top sections is exposed to notable regional differences. This can be explained by the fact that the stem form in the middle section can be more influenced by crown length than by other site and environmental conditions (Larson 1963; Courbet 1999; Muhairwe 1994, 1999). A tree with a longer crown will exhibit a greater rate of taper than a

¹The IP is the point where the neiloidal form of the butt section changes to a parabolic or paraconic form, and the r begins to be lower than 1.

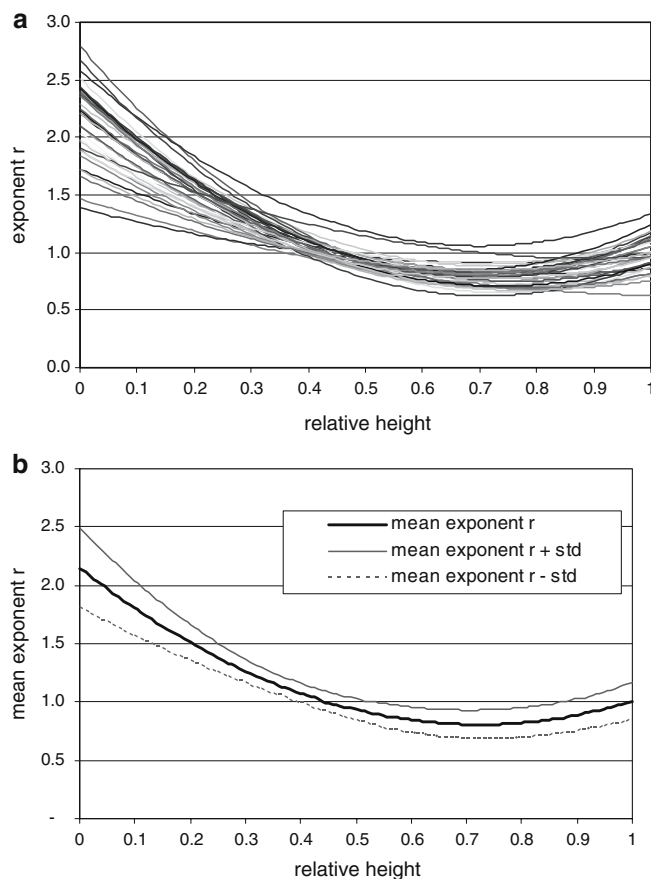


Fig. 2 **a** Exponents (r) of all guns, and **b** mean r with SD (std) by relative height

tree with a shorter crown length. Small regional differences in taper of the middle stem sections can also be partly caused by the low precision in estimating stem form in the middle stem section. Many stem taper models including Lee's model achieve the poorest statistical performance at 65–85% of total height (Max and Burkhart 1976; Kozak 1988; Newnham 1992; Figueiredo-Filho et al. 1996; Muhairwe 1999; Lee et al. 2003).

Relationship between traditional delimitation and new clusters

Uyeki (1928) identified two primary ecotypes within our study region: the Keumkang ecotype with conical tree crowns and the central southern lowland ecotype with non-straight tree boles and wide crowns (Fig. 1b). We performed a cluster analysis on our stem form indices to see if two clusters representing the two primary ecotypes were sufficient for explaining stem form over the study area.

Cluster analysis was performed with the method of WARD in CLUSTER procedure of SAS and with the variables of the stem form indices at butt ($r005$) and top sections ($r09$), and IP. We used a majority rule (the most frequently occurring ecotype within the cluster) to label the clusters. For example, in the cluster analysis based on

$r005$, cluster 1 is made up of 22 guns of which 15 belong to the central eastern region and the other seven originated from the central western region. So cluster 1 was labeled the “central eastern cluster” (CE). Cluster 2 includes 17 guns of which 13 belong to the central western region, so it was labeled the “central western cluster” (CW).

We developed an error matrix for the cluster classification of the style used in remote sensing studies (Story and Congalton 1986). The error matrix calculates producer's, user's and overall accuracy (Table 2). Out of 19 guns in the traditional central eastern region, 13–15 guns comprising 68–79% of the 19 guns are classified into the CE. About 60–70% of guns in the traditional central western region are classified into the CW. As a whole, about 69–72% of the guns in the traditional growth regions were correctly classified.

Figure 3 shows the user's accuracy of the cluster classification. In the case of a cluster analysis with $r005$, 22 guns are classified into the CE and the other 17 guns are assigned to the CW. 15 guns out of 22 guns of CE belong to the traditional central eastern region. And 13 guns out of 17 guns of CW belong to the traditional central western region. About 60–68% of the guns in CE comprise the guns of the traditional central eastern region, and about 70–77% of the guns in CW comprise the guns in the traditional central western region. These results indicate that the traditional delimitation for the stem form of red pine can be deemed as meaningful and acceptable. Kim et al. (1995) classified ten populations of red pine into two groups and concluded that the populations were not classified into the traditional six groups.

Comparison of stem forms of the new clusters with the traditional tree forms

Assuming that CE represents central eastern region and CW represents central western region, the means of r are calculated for each cluster and shown in Fig. 4a with its corresponding taper curve in Fig. 4b. Distinctive differences in average stem form between the eastern and western region can be noted in Fig. 4. In the butt section, the stem of the western region tends to be more tapered (more conical) than that of the eastern region, whereas the upper part stem of the western region tends to be less tapered (more cylindrical) than that of the eastern region.

From the comparison of Fig. 4 with Fig. 1b, it can be inferred that the average stem form of CE is consistent with that of the Keumkang ecotype, while the average stem form of the CW is consistent with that of the central southern lowland ecotype. Long crown length like that found in the Keumkang ecotype in Fig. 1b is in general combined with a tapered (conical) stem in the crown section. The short crown length of the central southern lowland ecotype is of relevance to the relatively long clear stem length that can result in a cylindrical stem form at the middle or upper stem section.

Regional distribution of the new clusters

Figure 5 shows the spatial distribution of two clusters for various taper indices. Most of the guns of CE are located in the central eastern region, while most of the guns of CW are located in the central western region. It is notable that stem forms in some of the eastern coastal region are categorized into the western region cluster. Lee et al. (1997) also reported that the populations which are geographically close did not show a tendency to cluster into the same group.

These regional variations in stem form can be related to the differences in genetic structure, silvicultural treatment, microhabitats, growth history, environmental and climatic factors, etc. However, our analysis was limited to the geographic and climatic factors, and other factors such as genetic traits, silvicultural treatment, microhabitats, growth history were excluded in this study. This study was designed to develop first the stem form indices and then identify the regional differences in stem form with the help of these and further investigate whether the regional differences in stem form are related to climatic factors. The special emphasis of this study has been placed on an examination of which climatic factors exert a statistically significant influence on stem form at the butt, middle and top section, and whether the statistically significant influence of climatic factors on the stem form can be considered biologically meaningful.

Geostatistical analysis of regional differences in stem form indices

Spatial autocorrelation analysis (variogram) of the stem form indices

Figure 6 shows the spherical variogram models for various stem form indices at the butt section ($r005$), top section ($r09$), IP, and $rmin$. Spatial autocorrelation is present in these indices as judged from the empirical variograms in Fig. 6. This implies that the trees in neighboring guns are similar in form. Spatial autocorrelation exists within a range of approximately

50–80 km. Beyond that range there is no discernable spatial autocorrelation in stem form indices.

Spatial interpolation (kriging) of stem form indices

Ordinary kriging of stem form indices was performed with the above empirical variogram models. The resulting kriging predictions are presented in Fig. 7. The value of $r005$ tends to be lower in the eastern upland, and higher in the western lowland and the eastern coastal region. This implies that the stem form in the butt section tends to be less tapered (more cylindrical) in the eastern upland and more tapered (more conical) in the western lowland and the eastern coastal region as depicted in Fig. 1b.

In comparison to $r005$, the value of $r09$ tends to be higher in the upland, and lower in the western lowland and the eastern coastal region. Thus, stem form in the top section tends to be more tapered (more conical) in the eastern upland and less tapered (more cylindrical) in the western lowland and the eastern coastal region. The contour map of IP and $rmin$ shows that stem form in middle section is more tapered (more conical) in the eastern upland than in the western lowland and the eastern coastal region.

Relationship between stem forms and climatic indices

Spatial regression and statistical significance

Spatial regression analysis with independent variables of climatic factors was performed with various maximum distances, using S+SPATIAL STATS module of SPLUS. Spatial neighbors using nearest neighbors with Euclidean metrics were determined using a number of different maximum distances (50, 80, 100, 150, 200, and 250 km). Spatial regression using a maximum distance of 100 km for spatial neighbors performed the best and is presented below. First warmth index (WI), mean precipitation and wind speed for the period of WI were employed as independent variables. Regression parameters are possibly indicative of the relationship between

Table 2 Number of guns classified into each cluster and producer's accuracy (PA)^a in parentheses. OA Overall accuracy, $r005$ exponent at relative height of 0.05, $r09$ r at relative height of 0.9, IP inflection point

Growth regions	Total number of guns	Variable for cluster analysis			
		$r005^c$	$r09^d$	$r005 + r09$	$r005 + r09 + IP^e$
Central eastern	19	15 (79)	15 (79)	15 (79)	13 (68)
Central western	20	13 (65)	12 (60)	12 (60)	14 (70)
Total OA ^b	39	28 (72)	27 (69)	27 (69)	27 (69)

^aPA = (no. of guns correctly classified in a region/total no. of guns traditionally classified in the region)×100

^bOA = (total no. of guns of correct classification/total no. of guns)×100

^cRepresents the stem form at the butt section

^dRepresents the stem form at the top section

^eRepresents the stem form at the middle section of the stem

Fig. 3 Number of guns correctly classified in a region (*Correct*) and total number of guns actually classified in the region (*Total*), and user's accuracy ($\text{Correct/Total} \times 100$). *CE* Central eastern cluster, *CW* central western cluster, *r005* *r* at relative height of 0.05, *r09* *r* at relative height of 0.9, *IP* inflection point

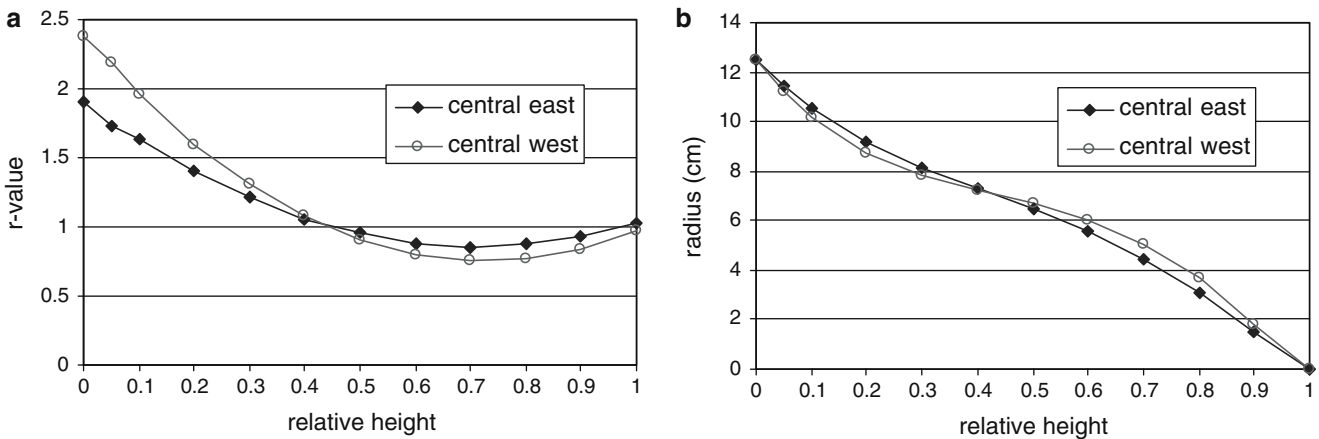
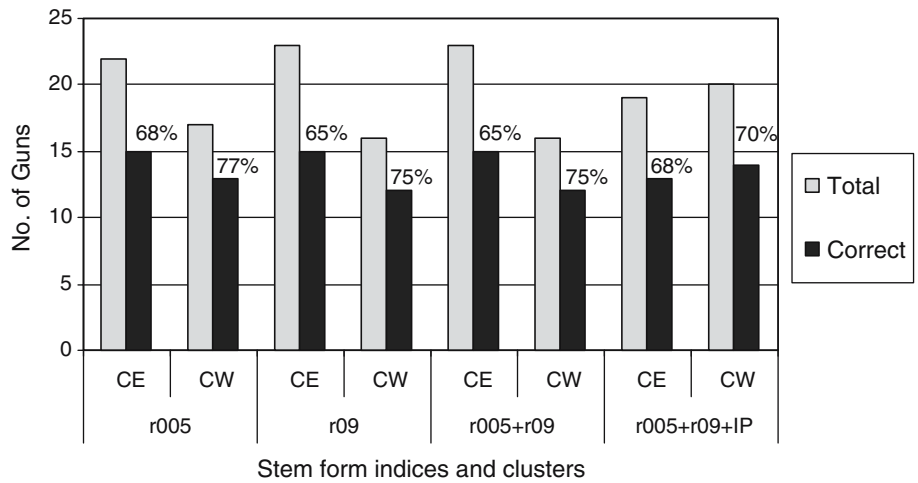


Fig. 4 Mean *r* for the central eastern and western regions (a) and corresponding taper curves (b)

variables. For identifying which climatic factors have a statistically significant influence on stem form, variables that have significance levels that are less than $\alpha=0.01$ are selected and their coefficient estimates are listed in Table 3.

For *r005*, precipitation is significant, and WI is significant for *r09*. Precipitation and wind are significant for IP and *r*_{min}. Although some climatic factors can be identified which exert a statistically significant influence on stem form, this does not guarantee that the results are biologically meaningful. For a more detailed analysis, seasonal climatic indices for non-growing season (November–February), early growing season (March–June) and late growing season (July–October) are employed as independent variables, and the variables whose significance levels are less than $\alpha=0.01$ are selected (Table 4).

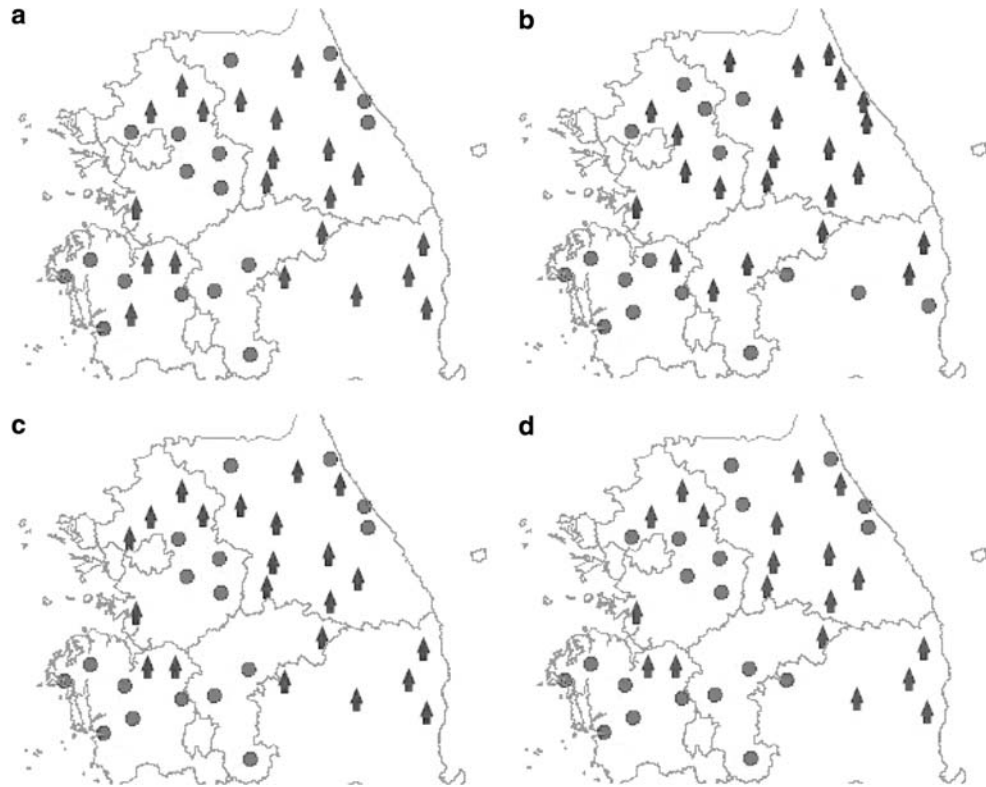
Statistically, the spatial regression model shows better performance with a lower residual SE than the traditional linear regression model with ordinary least squares estimation (OLS). The reported spatial regression model

also gives better biological interpretability resulting in more variables being significant.

For the stem form at butt section (*r005*) only the variable of precipitation during the late growing season (PSU) is significant. The precipitation during the late growing season has a positive relationship with the *r005*, which implies that high levels of precipitation are associated with high values of *r005* and this results in trees being “more tapered” at the butt section. The coastal region shows higher precipitation during the late growing season and this results in trees being “more tapered” at the butt section than in the eastern upland (Fig. 8, PSU).

For the stem form at the middle section (*r05*), temperature during the non-growing season, precipitation during the growing season, and wind during the late growing season are significant in the spatial regression model. Notable is that wind during the late growing season has a negative relationship with *r05*. Higher wind speed causes lower *r05*, which results in less tapering in the middle section of the stem. The coastal region shows higher wind speed in summer which results in trees that

Fig. 5 Distribution maps for two cluster groups with $r005$ (a), $r09$ (b), $r005 + r09$ (c), and $r005 + r09 + IP$ (d). Circles indicate the guns classified into the central western cluster, and arrows indicate the guns classified into the central eastern cluster. For abbreviations, see Fig. 3



are “more cylindrical” in the middle section than tree in the eastern upland region (Fig. 8, WSU).

For the stem form at the top section ($r09$), the variables of temperature during the non-growing season and late growing season, precipitation in all seasons, and wind during the late growing season are significant. Temperature and WI have a negative relationship with stem form. With higher temperatures, $r09$ has lower value which causes trees to be more cylindrical in the top section. The temperature and WI of the central western region and of both coastal regions, where the stem form in the top section is more cylindrical, are higher than those of the eastern upland region (Fig. 8, WI). Precipitation during the non-growing season has a positive relationship with the $r09$ coefficient, while precipitation during the growing season has a negative relationship. High precipitation during the growing season causes low values of $r09$ resulting in less tapered top sections of trees. In the western lowland and coastal area, where the stem form in the top section is less tapered, high precipitation during the growing season is observed (Fig. 8, PSU). It is controversial that precipitation in the non-growing season has a positive relationship with the stem form of the top section. High precipitation during the non-growing season brings about high values of $r09$ resulting in more tapered top sections of trees. The eastern upland, where the stem form in the top section is more tapered, usually records high precipitation in winter (Fig. 8, PWI). Wind during the late growing season exerts a significant effect on stem form of the top section.

Higher wind during the late growing season causes the lower value of $r09$, which results in the top section of the stem being more cylindrical in shape. Both coastal regions experience higher wind than the eastern upland region regardless of season (Fig. 8, WSU).

For the IP and $rmin$ indices, precipitation during the growing season and temperature during the non-growing season are significant and show a negative relationship with the stem form indices. Low precipitation during the growing season causes high IP and $rmin$ values and results in trees with more taper in the middle and upper stem sections. The eastern upland region experiences lower precipitation during the growing season and hence is more tapered in the middle and upper stem sections than trees in the western lowland region (Fig. 8, PSU).

Biological coincidence

Stem form differences in butt section Through spatial regression, several climatic factors proved to exert a meaningful influence on stem taper form. For stem form at the butt section, the precipitation during the late growing season exerts a statistically significant effect. High precipitation during the growing season in the western lowland and coastal region causes the stem form at the butt section to be more tapered.

Swell at the butt section in the western region can be attributed to a heavier load (Courbet 1999) which is in general traced to wide crown width (Larson 1963), root

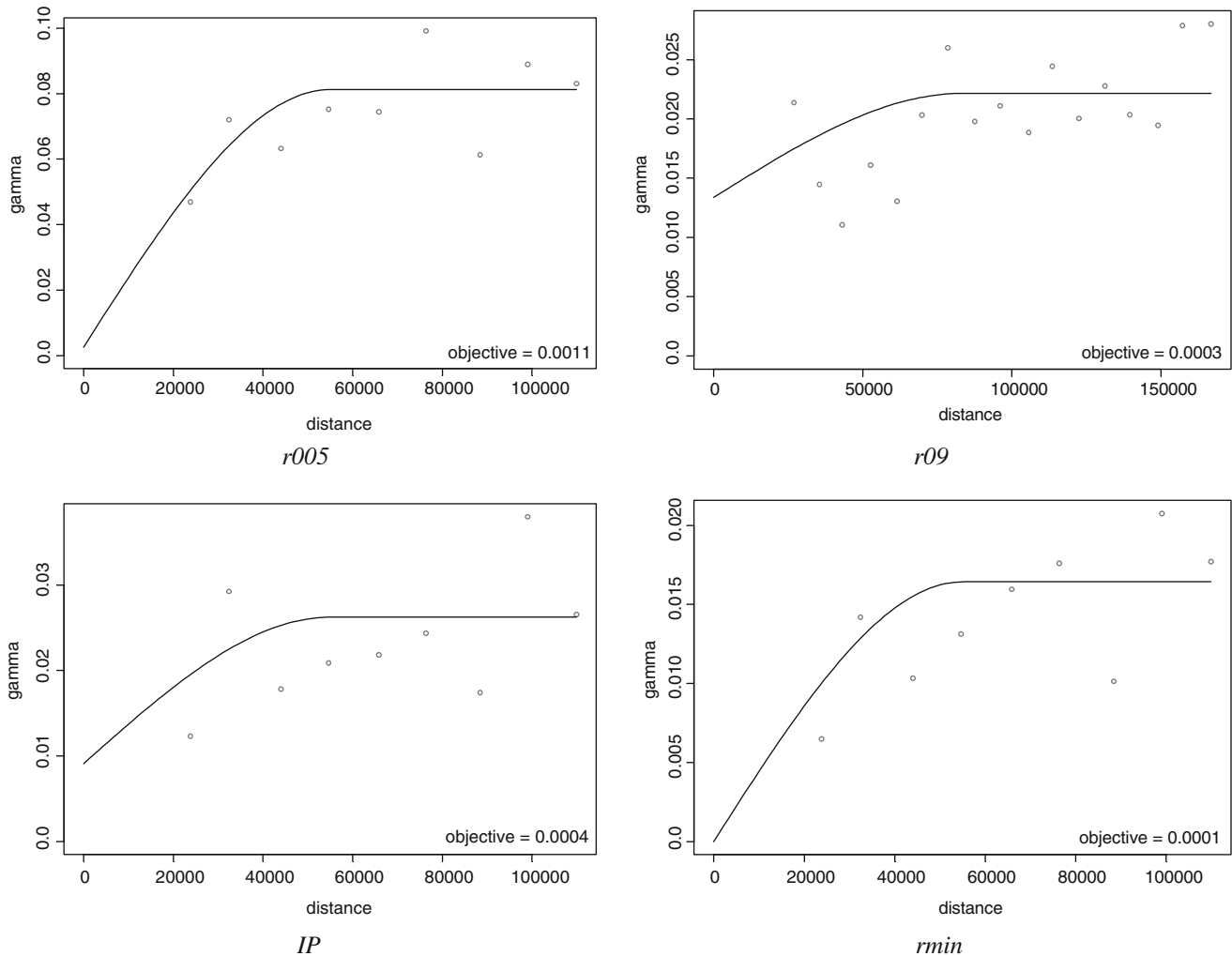


Fig. 6 Variogram of stem form indices at butt section (*r005*), top section (*r09*), IP, and minimum *r* (*rmin*). For other abbreviations, see Fig. 3

anchorage system (Nicoll and Ray 1996; Karlsson 2000) and wind pressure (Wilson 1975; Telewski 1995; Nicoll and Ray 1996).

Courbet (1999) pointed out that bigger and heavier trees must be more flared at the base in order to ensure stability. Short crown length and wide crown width in the western region (Chuncheonamdo 2001; see also Fig. 1b) can also impose a heavier load on the butt section.

Nicoll and Ray (1996) and Karlsson (2000) report that basal swell also occurs in sandy and stony coastal soils where tree anchorage is problematic. This may account for the positive relationship between *r005* and precipitation we observed during the late growing season. It is possible that increased precipitation in this period increases soil moisture to the point of creating an unstable environment for tree anchorage, which tends to increase butt swell.

Wind pressure can also cause the swell at the butt section through thickening of the lower stem (Jacobs 1954; Valinger 1990; Robertson 1991; Nicoll and Ray 1996), or equalizing wind stress along the stem (Larson

1965; Wilson and Archer 1979; Morgan and Cannell 1994; Ennos 1995). In this study, however, wind appeared to exert no statistical significant influence on the stem form at butt section. But wind can practically exert indirect influence on stem form at the butt section in the way that the wind affects short crown length and wide crown width causing the tapered butt section (Kwak et al. 2004).

Stem form differences in middle and upper section Temperature and precipitation during the growing season, and wind during the late growing season together have statistically meaningful influences on the stem form in the middle and upper sections. High temperature, precipitation, and wind during the growing season in the western lowland and coastal region together bring about a more cylindrical stem form in the middle and upper sections.

A more cylindrical stem form in the middle and upper sections of trees in the coastal region can be attributed to

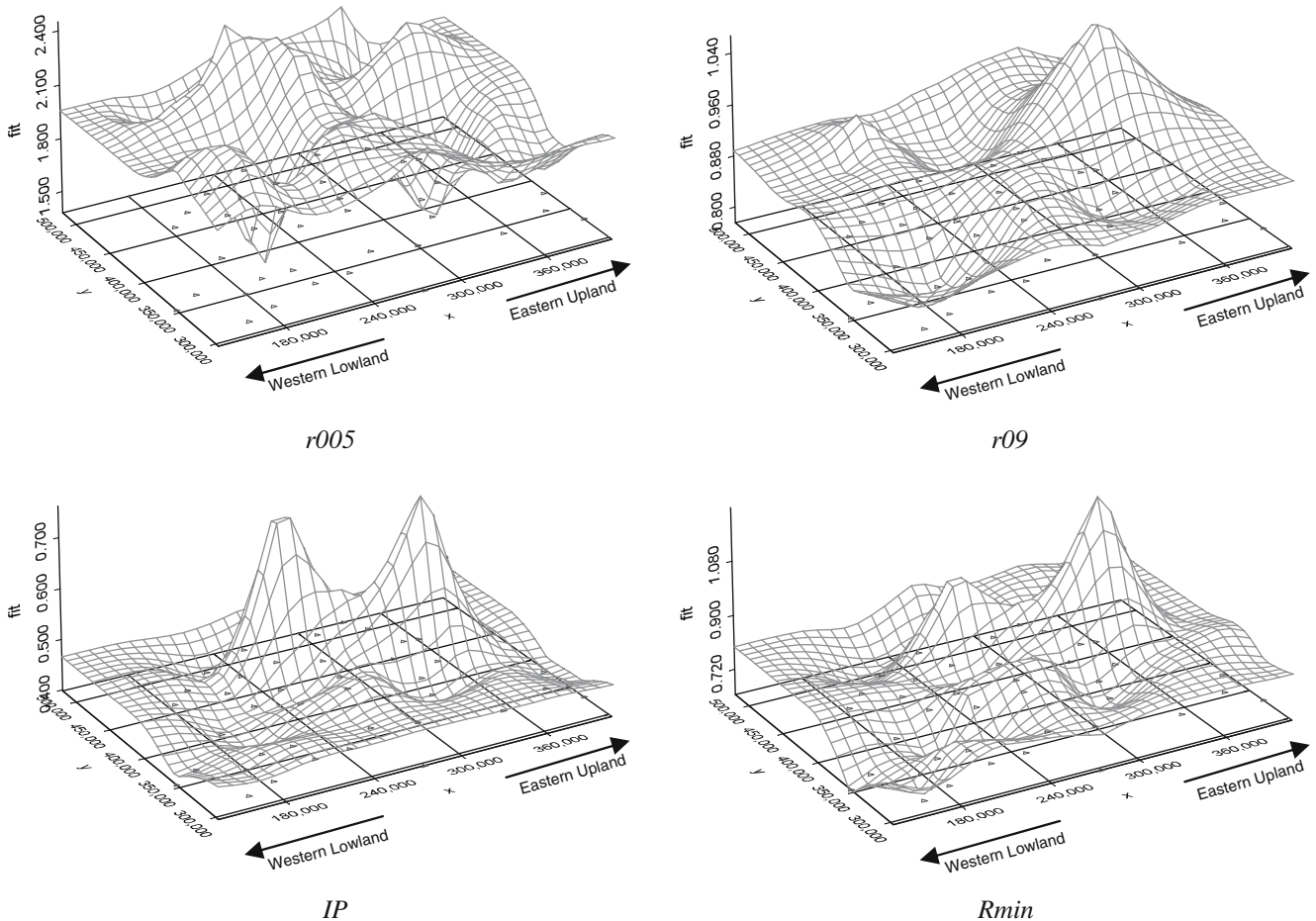


Fig. 7 Kriged 3D contour map for stem form indices at butt section (*r005*), top section (*r09*), *IP*, and *rmin*. For abbreviations, see Figs. 3 and 6

Table 3 Coefficients and their significance level in spatial regression between stem form indices (*SFI*) and climatic factors. *WI* Warmth index, P_{WI} mean precipitation during the period of *WI*, W_{WI} mean wind speed during the period of *WI*, *rmin* minimum *r*

SFI	<i>r005</i>		<i>r05</i>		<i>r09</i>		IP		<i>rmin</i>	
	Value	$P(> t)$	Value	$P(> t)$	Value	$P(> t)$	Value	$P(> t)$	Value	$P(> t)$
WI	–	NS	–	NS	–0.0027	0.1091	–	NS	–	NS
P_{WI}	0.0079	0.0001	–	NS	–	NS	–0.0016	0.0609	–0.0016	0.0939
W_{WI}	–	NS	–0.0675	0.0275	–	NS	–0.0737	0.0537	–0.0636	0.1065

the fact that high wind loads at the coast cause trees to sway, and swaying generally results in an allocation of growth to the lower parts of the stem (Valinger 1990; Karlsson 2000). Trees being cylindrical can be also traced to shorter crown length in the western region. Pressler's law (Pressler 1864) states that ring area growth at any one point on the stem is proportional to the quantity of foliage above this point. Thus, ring area growth will be the same in all parts of the branch-free stem. This theory helps explain why a tree with a small crown has a more cylindrical stem (Larson 1963).

Crown length, which plays a decisive role as a determinant of stem form (Larson 1963), can be affected

by the wind. The pressure exerted by the wind on the tree crown can lead to structural stem failure such as bending and torque (Jones 1992). Rees and Grace (1980a, b) reported that height growth of *Pinus contorta* was reduced by the shaking effect of the wind, but radial growth was unaffected. Karlsson (2000) also reported that the height growth pattern for coastal pine exhibited a strong stagnation, which can be attributed to high wind loads at the coast of Finland (Valinger 1990; Karlsson 2000). According to Telewski (1995), in most cases where trees are under wind-induced swaying there is a decrease in height growth, but an increase in diameter growth.

Table 4 Coefficients and their significance level in spatial regression between stem form indices and climatic factors. *TWI* Temperature during the non-growing season (November–February), *TSP* temperature during the early growing season (March–June), *TSU* temperature during the late growing season (July–October), *PWI* precipitation during the non-growing season, *PSP* precipita-

tion during the early growing season, *PSU* precipitation during the late growing season, *WSU* wind speed during the late growing season, *NS* not significant, *RSE* residual SE [$RSE\% = (RSE/\text{mean}) \times 100$], *OLS* ordinary least squares estimation; for other abbreviations, see Tables 2 and 3

Regression model	Coefficient	<i>r</i> 005		<i>r</i> 05		<i>r</i> 09		IP		<i>r</i> min	
		Value	<i>P</i> (> <i>t</i>)	Value	<i>P</i> (> <i>t</i>)	Value	<i>P</i> (> <i>t</i>)	Value	<i>P</i> (> <i>t</i>)	Value	<i>P</i> (> <i>t</i>)
	Mean	1.97		0.93		0.89		0.47		0.80	
Spatial model with temperature index ^a	<i>TWI</i>	–	NS	–0.0324	0.0636	–0.0707	0.0096	–0.0506	0.0467	–0.0737	0.0021
	<i>TSU</i>	–	NS	–	NS	–0.0158	0.0544	–	NS	–	NS
	<i>PWI</i>	–	NS	–	NS	0.0130	0.0009	–	NS	0.0080	0.0135
	<i>PSP</i>	–	NS	–0.0030	0.0682	–0.0064	0.0142	–0.0063	0.0119	–0.0075	0.0009
	<i>PSU</i>	0.0038	0.0012	–0.0008	0.0143	–0.0009	0.0890	–0.0019	0.0004	–0.0023	0.0000
	<i>WSU</i>	–	NS	–0.1296	0.0832	–0.2227	0.0444	–	NS	–	NS
	<i>RSE</i>	0.2384		0.0713		0.1073		0.1023		0.0929	
	<i>RSE%</i>	12.1		7.7		12.1		21.8		11.6	
Spatial model with WI ^b	<i>WI</i>	–	NS	–	NS	–0.0045	0.0429	–	NS	–	NS
	<i>PWI</i>	–	NS	–	NS	0.0091	0.0266	–	NS	–	NS
	<i>PSP</i>	–	NS	–0.0030	0.0625	–0.0074	0.0039	–0.0052	0.0269	–	NS
	<i>PSU</i>	0.0035	0.0012	–0.1787	0.0156	–	NS	–0.0011	0.0371	–0.0016	0.0390
	<i>WSU</i>	–	NS	–	NS	–0.3700	0.0017	–	NS	–	NS
	<i>RSE</i>	0.2320		0.0833		0.1280		0.1251		0.1072	
	<i>RSE%</i>	11.8		9.0		14.4		26.6		13.4	
Linear model with OLS	<i>PWI</i>	–	NS	–	NS	0.0072	0.0934	–	NS	–	NS
	<i>PSU</i>	0.0031	0.0577	–	NS	–	NS	–	NS	–0.0012	0.0474
	<i>WSU</i>	–	NS	–	NS	–0.2089	0.0767	–	NS	–	NS
	<i>RSE</i>	0.3337		0.1008		0.1391		0.1288		0.1192	
	<i>RSE%</i>	16.9		10.8		15.6		27.4		14.9	

^aStem form index = $a \times TWI + b \times TSP + c \times TSU + d \times PWI + e \times PSP + f \times PSU + g \times WWI + h \times WSP + i \times WSU$

^bStem form index = $a \times WI + b \times PWI + c \times PSP + d \times PSU + e \times WWI + f \times WSP + g \times WSU$

The high wind speed at the coast, especially in summer, can cause the new stem of top sections to bend before being hardened during the late growing season. Downwind bending at the top section can be easily found in the western coastal region (Chungcheongnamdo 2001). The bending of the new stem at the top section makes the tree height almost constant, so that the tree height growth in the western coastal region declines earlier, whereas the stem height to the base of live crown steadily increases (Chungcheongnamdo 2001; Kwak et al. 2004). The acclimatization of red pine to high wind causes short crown length and cylindrical stem form at middle and upper stem sections in the coastal region.

Recommendations for further research

In this study only climatic factors are investigated for explaining regional variation in stem form. Spatial regression improved our ability to identify the relationship between stem form and climatic factors over traditional OLS regression (see Table 4). Residual SE values were reduced and statistically significant coefficients for temperature, precipitation and WI (see Table 4) were obtained in the spatial regression. However, there still exists unexplained variation which might be further reduced by the inclusion of other factors. That is, although regional variation in stem form characteristics

was shown to be related to climatic factors, additional factors (genetic traits, silvicultural treatments, microclimate, topography, soil and age, etc.) and growth history need to be considered in further investigation.

Several studies on differentiation of genetic traits of red pine have been reported for Korea (Kim and Lee 1992; Kim et al. 1993, 1995, 2005; Lee et al. 1997; Kim and Han 1997). Kim and Lee (1992) and Kim et al. (1993) reported that *P. densiflora* for. *erecta* (Keumkang ecotype) in the central western region cannot be treated genetically as a distinct group from other natural populations of *P. densiflora*. These results also suggested that populations of red pines in the central western Korea have been much differentiated morphologically but not enough genetically to be treated as a distinct genetic group. Kim et al. (1995) reported that ten populations of red pine showed different genetic structures and that they were classified into two genetic groups instead of being classified as six traditional geographic groups. Lee et al. (1997) also reported that the populations which were close geographically did not show a tendency to cluster into the same group. Environmental variability of the provenances was also reported to exert an influence on the survival rate and height growth (Kim and Han 1997; Kim et al. 2005). Regarding these studies, we can recognize that the geographical variation in stem form of red pine can be attributed to genetic traits and silvicultural treatment as well as environmental vari-

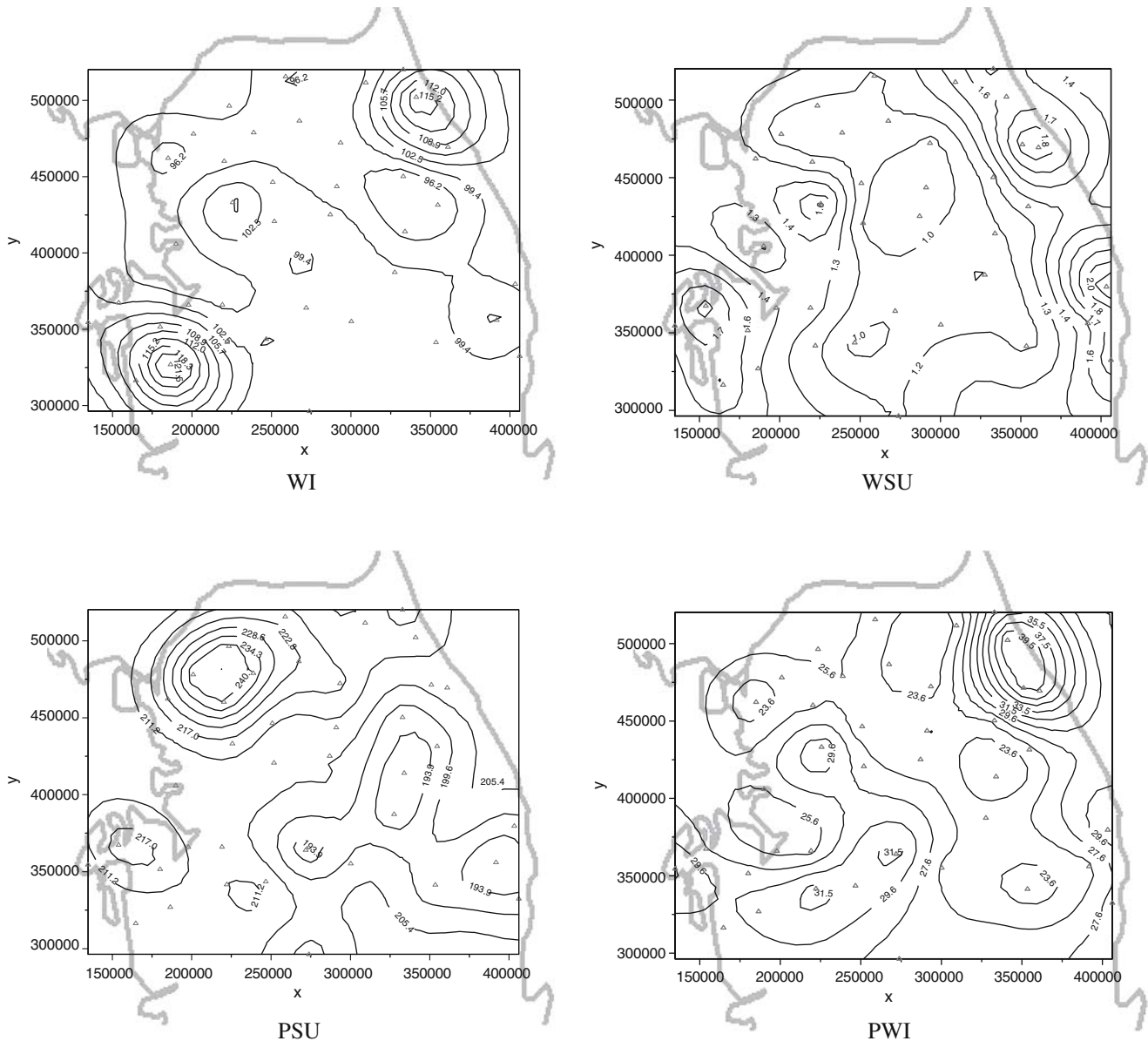


Fig. 8 Kriged contour map for climatic factors of warmth index (*WI*), wind during the late vegetation period (*WSU*), precipitation during the late vegetation period (*PSU*), and precipitation during the non-vegetation period (*PWI*)

ability. To incorporate these factors into further studies, an analysis should be done for each sample plot in which other relevant genetic, silvicultural and environmental factors are available (Morris and Forslund 1992).

In the research reported here we were restricted to analyzing information based on administrative units (guns) which averaged 80,000–150,000 ha in size. This precluded us from examining the influence of site-based factors on stem form.

In this study only 5 years of data were available to investigate the influence of climate on stem form. However, stem form at a given moment is the result of the long-term response of trees to the growing condition or changing environment. It is preferable to investigate the stem form with changing forest conditions from a longer

time period. Also there is a need to precisely examine the mechanism of how changing forest conditions affect stem form for a long period and how the tree is acclimatized to changing climate and stand conditions.

Conclusion

This study verified that regional differences in stem form exist in central Korea and we were able to identify the relationship between stem form and climatic factors through the use of spatial regression.

Regional differences can be well verified by using stem form index for the butt or top stem section. In comparison to stem form in the eastern upland, the

stem form in the western lowland is characterized by trees with more conical-shaped butt sections and more parabolic shaped middle and top sections. We were able to show through cluster analysis that the traditional ecotypes of Keumkang and central southern lowland were reasonably good for the identification of regional differences in stem form. However, we were able to improve on this simple classification by using geostatistical analysis of ordinary kriging and spatial regression to predict stem form as a function of climatic variables.

The stem form at the butt section has a statistically significant positive relationship with the precipitation during the late growing season. The western lowland and both coastal regions experience higher precipitation during the late growing season and experience more tapering at the butt section than in the eastern upland.

For the stem form in the middle and upper tree sections, the variables of temperature or WI, precipitation in all seasons, and wind during the late growing season are significant. Temperature and WI have a negative relationship with stem form in the upper section. The temperature and WI of the central western region and both coastal regions, where the stem at the top section is more cylindrical, is higher than that of the eastern upland. Precipitation during the non-growing season has a positive relationship with the stem form in the upper section. The eastern upland, where the stem form in the top section is less tapered, experiences generally higher precipitation in winter. Low precipitation during the growing season causes more tapering in the middle and upper sections of the stem. The eastern upland has lower precipitation during the growing season and more tapering in the middle and upper sections of the stem than occur in the western lowland. Wind during the late growing season exerts a significant effect on stem form of the top section. Higher wind during the late growing season causes the stem form at the top section to be more cylindrical. Both coastal regions, where the stem form in the upper section is more cylindrical, experience higher wind than the eastern upland.

Swell in the butt section of trees in the western and coastal region can be attributed to heavier load in the butt section, which is in general traced to wide crown width, wind pressure, root anchorage system, and sandy or stony soil. The more parabolic tree form in the middle and upper stem sections in the western lowland and the coastal region can be attributed to the short crown length caused by high wind speed and temperature.

Although the regional variations in stem form characteristics were shown to be related to climatic factors in this study, additional factors which exert an effect and growth history need to be considered in further investigations.

This study can be considered an initial investigation into the factors controlling stem form variability through central Korea. The results can be used to produce more accurate regional stem taper models needed

for the reasonable management of red pine stands in different regions.

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