ABSTRACT: Soil phosphorus (P) availability and fractions are influenced to a large extent by land use and cover changes. Inorganic P (IP) and organic P (OP) fractions in surface soils (0–20 cm) under typical vegetation types, including subalpine coniferous forests, alpine shrubs, and alpine shrub-meadows, near the alpine timberline of the eastern Tibetan Plateau of China, were measured by a modified Hedley fraction method. The results showed that OP is the dominant soil P fraction and the main source of available P in alpine soils near the timberline. Soil organic carbon, total nitrogen, and total P contents were higher in subalpine coniferous forests than in alpine shrubs and alpine shrub-meadows. Concentrations of soil labile P (the sums of Resin–IP, NaHCO₃–IP, and NaHCO₃–OP) were higher in subalpine coniferous forests than in alpine shrubs and alpine shrub-meadows, an observation that may be partially ascribed to the presence of deep litter layers generated by trees. Concentrations of soil labile and moderately organic P (NaHCO₃–OP and NaOH–OP) in subalpine coniferous forests were also greater than in alpine shrubs and alpine shrub-meadows. Greater amounts of soil stable OP (extracted by concentrated HCl and cHCl–OP) were accumulated in alpine shrub-meadows compared to alpine shrubs or subalpine coniferous forests. The reduced availability of OP may be attributed mainly to increasing recalcitrant soil organic matter input in alpine shrub-meadows and alpine shrubs. Concentrations of IP associated with Ca minerals and parent materials (extracted by diluted HCl and HCl–IP, and extracted by concentrated HCl and cHCl–IP, respectively) were lower in subalpine coniferous forests, indicating that coniferous forests are more likely to use recalcitrant IP than alpine shrubs and alpine shrub-meadows. In this alpine region, land cover changes from subalpine coniferous forests to alpine shrubs and alpine shrub-meadows near the alpine timberline could decrease soil P conservation, availability, and supplementation.

KEY WORDS: phosphorus availability, phosphorus fractions, vegetation type, alpine timberline, Tibetan Plateau

1. INTRODUCTION

Phosphorus (P) is one of the nutrients essential for maintaining alpine ecosystems (Aerts and Chapin 2000) and is assumed to be the limiting or co-limiting factor for primary productivity in alpine environments (Bowman 1994, Theodoxe and Bowman 1997). Unlike the nitrogen (N) cycle, which is influenced by atmospheric deposition, the P cycle is a closed cycle through plant residues and soil organic matter (SOM) (Cross and Schlesinger 1995, Litaor et al. 2005). Soil P fractions with different bioavailabilities...
exist in equilibrium with each other through
soil P transformation processes involving
the mineralization-immobilization of or-
ganic P (OP), adsorption-desorption, and
the precipitation-dissolution of inorganic P
(IP) (Frossard et al. 2000). Biogeochemical
studies of soil P in alpine regions indicate that
soils accumulate large amounts of OP due to
SOM sequestration under low average tem-
peratures. Slower weathering rates in the par-
ent material also influence soil P pools and
its availability (Beck and Elsenbeer 1999,
Parker and Sanford 1999, Litaor et al.
2005). Therefore, available P is usually scarce
and regarded as one of the limiting factors of
vegetation in the alpine region of the eastern
Tibetan Plateau (Liu et al. 2004).

Although low temperatures and freeze-
thaw cycles control soil ecological processes in
alpine regions (Cassagne et al. 2000, Litaor
et al. 2005), plants also exert significant effects
on soil P availability and fractions through
litterfall, root turnover and exudation, and
interactions with microbes (Cross and
Schlesinger 1995, Cassagne et al. 2000,
Shiels and Sanford 2001). Timberlines are
boundaries of different alpine and subalpine
ecosystems, where the vegetation types change
dramatically within a small altitudinal gradient
and a short distance (Kammer et al. 2009).
Some research has been done on the effects of
different types of vegetation on soil nutrient
pools and their transformation rates. Com-
paring soils in forests with soils of tundra near
timberlines, the SOM and total N of forest
soils were found to be higher than that of tund-
ra soils, and the C and net N mineralization
were increased (Kammer et al. 2009). Shiels
and Sanford (2001) found that krummholz
forests had higher available P concentrations
than tundra soils. However, few systematic
studies report on whether or not and how in-
tact vegetation types, such as subalpine conif-
erous forests, alpine grasslands, or shrublands,
affect the dynamics of soil P availability and
fractions in high altitude zones.

On the eastern Tibetan Plateau, the lower
part of the mountains is covered by subalpine
coniferous forests. Above the timberline, the
vegetation changes into alpine shrubs and
alpine shrub-meadows due to arid and frig-
id environmental conditions (Gao and Li
2000). Although both subalpine and alpine
ecosystems of the Tibetan Plateau are consid-
ered to be sensitive to global change and hu-
man activities, few researchers have focused
on the timberline ecotone in this region (Wu
and Liu 1998). In recent decades, the disap-
pearance of intact forests due to human dis-
turbances, such as logging, fires, and clearing
for pasture, or food crops, has caused tim-
berlines to decrease and alpine ecosystems
to degenerate (Wu and Liu 1998). These
changes, from subalpine coniferous forests to
alpine shrubs or alpine shrub-meadows near
the timberline, are similar to a gradient alpine
ecosystem degeneration and its deforestation
(2005) showed that the clearing of subalpine
forests for pasture and cropland has led to
a decrease in SOM and N₂O, and an increase
in CO₂ flux rates. However, little is known
about P status in different land covers. Stud-
ies on soil P regimes of subalpine forests with
adjacent alpine meadows or shrub-lands near
the timberline ecotone are important not only
for understanding the biogeochemical cycle
of P in intact vegetation but also for manage-
ing and monitoring vulnerable ecosystems in
this region. In this study, soil P fractions and
associated soil properties were determined to
examine the impact of different vegetation
types near the timberline on the alpine soil
fertility status, particularly on P availability
and fractions.

2. MATERIALS AND METHODS

2.1. Site description and sampling

Field work was conducted in Songpan
County, Sichuan Province in southwestern
China (N 32°59', E 103°40'). This site, located
to the east of the Tibetan Plateau, is part of
the Minshan Mountains. It is 5 kilometers
away from the headstream of the Mingjiang
River. The region is covered with snow and
ice from October-November to April-May.
The average annual temperature is 2.8°C,
with a monthly mean temperature of ~7.6°C
in January and 9.7°C in July. The mean an-
nual precipitation is 718 mm, 72% of which
occurs in the period between June to August
(Sun et al. 2005).

The lower part of the study area is domi-
nated by coniferous forests (Abies faxoniana
Impact of alpine vegetation on soil phosphorus availability

Rehd. et Wils.), with a timberline ecotone between 3695 and 3715 m. Above the timberline, the coniferous forests transform into alpine shrubs and alpine shrub-meadows. The alpine shrub is predominated by *Rhododendron aganniphum* Balf. F. et K. Ward, while the alpine shrub–meadow is composed of *Kobresia setchwanensis* Hand.-Mazz. and many dwarf shrubs, such as *Sibiraea angustata* (Rehd.) Hand.-Mazz., *Spiraea alpina* Pall. Fl. Ross., and *Potentilla parvifolia* Fish. Ap. Lehm. The bedrock consists mostly of granite and metamorphic rocks. Soil near the timberline has been classified as Inceptisol and is characterized by low degrees of development (Gao and Li 2000).

We randomly established five typical plots of alpine shrubs and alpine shrub-meadows and four plots of subalpine coniferous forests adjacent to the timberline. The plot sizes were 1 × 1 m, 5 × 5 m, and 10 × 10 m for the alpine shrubs, alpine shrub-meadows, and subalpine coniferous forests respectively. Individual plots were placed at distances of at least 15 m from any other plot. The topography characteristics (i.e., the slope aspect, slope degree, and micro-topography) and vegetation coverage for plots in every vegetation type were fairly consistent. In November 2008, following the removal of the litter layer, surface mineral soil samples were extracted using a 20 × 8 cm PVC tube sampler in each plot, across the plot in diagonal manner. The soil samples were combined to give a composite sample for every plot. Meanwhile, the depth of the litter layer was randomly measured in 10 sites in all vegetation types.

2.2. Laboratory analyses

Freshly collected soil samples were dried for 24 h at 105°C. The weights of all the samples were measured before and after drying to determine the gravimetric soil water content of each sample (Shiels and Sanford 2001). The soil pH was determined in a 1:2 (w/v) soil/water suspension using a glass electrode. Soil organic carbon (SOC) and total N were determined by dry combustion using a Leco 1000 CHN analyzer. Aluminum (Al), iron (Fe), and calcium (Ca) in an acid-digested microwave extract were measured using inductively coupled plasma emission spectroscopy (ICPS, Shimadzu-7500, Japan). All elemental and general analyses were done in triplicate.

The microbial biomass P (MB–P) was extracted via the chloroform fumigation-extraction method using 0.5 M NaHCO₃ (pH = 8.5) as the extracting solution (Brookes et al. 1982). The extractable IP was determined via the ascorbic acid molybdenum blue method (Murphy and Riley 1962). The equation used to calculate MB–P was as follows: MB–P = Eₚ/0.4, where Eₚ was the difference of the IP between fumigated and unfumigated soil samples (Brookes et al. 1982).

Phosphorous was extracted using a modified sequential Hedley fractionation method (Hedley et al. 1982) as described by Tieszen and Moir (1993). A 0.5 g soil sample was passed through a 0.149 mm sieve and placed in a 50 mL plastic centrifuge tube. It was then sequentially extracted using anion-exchange resin, 0.5 M NaHCO₃ (pH 8.5), 0.1 M NaOH, 1 M HCl, and concentrated HCl (cHCl). After each extraction, the samples were centrifuged at 16000 × g for 15 min at 0°C, and the supernatant was passed through a 0.45 μm filter. The residual soil P remaining in the tubes was determined via extraction by boiling in a concentrated H₂SO₄–H₂O₂ mixture at 360°C. Aliquots from the filtered NaHCO₃, NaOH, and cHCl extracts were further digested with ammonium persulfate in an autoclave at 103.5 kPa and 121°C to convert all the dissolved P into orthophosphate, which was then measured as the total P. The IP and the total P in all the extracts were determined using a UV-2500 spectrophotometer (Shimadzu, Japan) and the ascorbic acid molybdenum blue method (Murphy and Riley 1962). The OP was calculated as the difference between the IP and the total P. Total P values were calculated from the sum of the individual fractions. These fractions provide a measure of the proportions of plant-available and refractory P. Plant-available P includes Resin–IP, NaHCO₃–IP, and NaHCO₃–OP. Resin–IP refers to P that is readily exchangeable as IP and is easily dissolved from the solid phases in the soil. The NaHCO₃ extractable fractions are associated with the surface of amorphous and some crystalline Al and Fe minerals. The NaHCO₃–OP fraction is easily mineralizable
and can contribute to plant-available P. The plant-available pool, also called labile P, is the most biologically available form of P. Refractory P includes all other fractions, namely, NaOH–IP, NaOH–OP, HCl–IP, cHCl–IP, cHCl–OP, and Residual–P. The NaOH–extractable P fraction contains secondary IP bound to Fe and Al compounds and moderately labile OP associated with humic acids. The HCl–IP fraction refers to P associated with calcium minerals. Extracts of P removed by cHCl comes from P that is bound toapatite, and cHCl–OP is too stable to mineralize within a short period of time. Residual–P represents the most recalcitrant form of P.

Cross and Schlesinger (1995) suggested that these fractions can also be used to separate forms of organically bound soil P from geochemically bound fractions. This means that all OP fractions (NaHCO$_3$–OP, NaOH–OP, and cHCl–OP) have a biological source, whereas the remaining IP fractions (including Residual–P) have a geochemical source.

2.3. Statistical analyses

One-way analysis of variance (ANOVA) was used to determine if there were significant differences in the P fractions and basic soil properties among the different vegetation types. The threshold for accepting statistical significance was set to 0.05. Statistically significant differences of means were determined by the post-hoc Duncan’s multiple test.


<table>
<thead>
<tr>
<th>Soil properties</th>
<th>ASM</th>
<th>AS</th>
<th>SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.4 ± 0.20 a</td>
<td>5.2 ± 0.10 b</td>
<td>4.6 ± 0.20 c</td>
</tr>
<tr>
<td>SOC (%)</td>
<td>9.0 ± 0.32 a</td>
<td>9.5 ± 0.53 b</td>
<td>11.3 ± 0.35 c</td>
</tr>
<tr>
<td>N (%)</td>
<td>0.5 ± 0.01 a</td>
<td>0.5 ± 0.010 b</td>
<td>0.6 ± 0.009 b</td>
</tr>
<tr>
<td>Fe (%)</td>
<td>2.8 ± 0.11 a</td>
<td>2.7 ± 0.08 a</td>
<td>2.9 ± 0.12 b</td>
</tr>
<tr>
<td>Al (%)</td>
<td>3.5 ± 0.11 a</td>
<td>3.5 ± 0.05 a</td>
<td>3.7 ± 0.17 b</td>
</tr>
<tr>
<td>Ca (%)</td>
<td>1.0 ± 0.08 a</td>
<td>0.8 ± 0.10 b</td>
<td>0.6 ± 0.09 c</td>
</tr>
<tr>
<td>MB–P mg kg$^{-1}$</td>
<td>12.7 ± 5.48 a</td>
<td>30.3 ± 6.41 b</td>
<td>60.5 ± 5.21 c</td>
</tr>
<tr>
<td>Soil water content (%)</td>
<td>36.2 ± 4.15 a</td>
<td>39.5 ± 3.23 a</td>
<td>43.8 ± 4.12 b</td>
</tr>
<tr>
<td>Litter layer depth (cm)</td>
<td>2.5 ± 0.40 a</td>
<td>8.7 ± 3.20 b</td>
<td>35.6 ± 5.50 c</td>
</tr>
<tr>
<td>C:N</td>
<td>18.2 ± 0.50 a</td>
<td>18.3 ± 0.30 a</td>
<td>17.8 ± 0.20 a</td>
</tr>
<tr>
<td>C:OP</td>
<td>178.5 ± 5.50 a</td>
<td>188.4 ± 6.20 a</td>
<td>169.7 ± 7.20 a</td>
</tr>
</tbody>
</table>

Note: Different letters along the row indicate significant differences between the means of the soil properties of the different vegetation types (Duncan’s multiple, $P = 0.05$). In addition, we used Pearson correlation coefficients to assess the relationships between P fractions and soil properties. The analyses were performed using SPSS 11.0 (SPSS, Inc. 2001).

3. RESULTS

The SOC, total N, MB–P, soil water content, and litter layer depth significantly decreased from subalpine coniferous forests to alpine shrub-meadows. The pH and Ca content were significantly lower in subalpine coniferous forests than in alpine shrubs and alpine shrub-meadows. The soil samples in the three vegetation types exhibited approximately identical C:N and C:P ratios. However, the C:N and C:P ratios for the subalpine coniferous forest soils were slightly lower (Table 1).

Concentrations of total P, NaHCO$_3$–OP, NaOH–IP, and NaOH–OP were significantly greater in subalpine coniferous forests than in alpine shrubs and alpine shrub-meadows, while HCl–IP, cHCl–IP, and cHCl–OP had the lowest amounts in subalpine coniferous forests (Table 2). The NaOH–OP fraction, accounting for an average of 46% of the total P, was the predominant OP form. The cHCl–IP fraction was found to be the largest IP fraction in the soil (Table 2). The soil samples in this study were characterized by a larger percent (mean = 65%) of total OP (Fig. 1a). Significantly greater total OP concentrations were found in subalpine coniferous forests compared to alpine.
Table 2. Mean values and standard deviations of the soil P fractions (mg kg⁻¹) of the three vegetation types: ASM – alpine shrub-meadows, AS – alpine shrubs, SCF – subalpine coniferous forests, OP – organic P, IP – inorganic P.

<table>
<thead>
<tr>
<th>P extract</th>
<th>ASM</th>
<th>AS</th>
<th>SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resin–IP</td>
<td>14.00 ± 1.02 a</td>
<td>15.64 ± 0.85 a</td>
<td>14.78 ± 1.38 a</td>
</tr>
<tr>
<td>NaHCO₃–IP</td>
<td>15.19 ±0.91 a</td>
<td>13.91 ± 0.89 a</td>
<td>15.69 ± 1.32 a</td>
</tr>
<tr>
<td>NaHCO₃–OP</td>
<td>30.83 ± 2.71 a</td>
<td>59.12 ± 2.48 b</td>
<td>73.62 ± 5.91 c</td>
</tr>
<tr>
<td>NaOH–IP</td>
<td>28.03 ± 1.35 a</td>
<td>27.49 ± 3.02 a</td>
<td>47.87 ± 3.65 b</td>
</tr>
<tr>
<td>NaOH–OP</td>
<td>326.12 ± 1.97 a</td>
<td>360.42 ± 5.20 a</td>
<td>505.76 ± 5.86 b</td>
</tr>
<tr>
<td>HCl–IP</td>
<td>50.39 ± 1.97 a</td>
<td>54.07 ± 1.63 a</td>
<td>40.01 ± 1.98 b</td>
</tr>
<tr>
<td>cHCl–IP</td>
<td>115.44 ± 5.54 a</td>
<td>83.21 ± 3.20 b</td>
<td>85.08 ± 1.79 b</td>
</tr>
<tr>
<td>cHCl–OP</td>
<td>148.61 ± 1.15 a</td>
<td>87.89 ± 7.45 b</td>
<td>86.50 ± 8.88 b</td>
</tr>
<tr>
<td>Residual–P</td>
<td>99.42 ± 6.01 a</td>
<td>100.18 ± 1.06 a</td>
<td>72.70 ± 3.11 a</td>
</tr>
<tr>
<td>Labile P</td>
<td>60.02 ± 4.37 a</td>
<td>88.66 ± 8.51 b</td>
<td>104.09 ± 11.46 c</td>
</tr>
<tr>
<td>Refractory P</td>
<td>768.01 ± 44.03 a</td>
<td>713.26 ± 65.56 a</td>
<td>837.92 ± 100.25 a</td>
</tr>
<tr>
<td>Total IP</td>
<td>322.47 ± 10.64 a</td>
<td>294.49 ± 9.33 ab</td>
<td>276.13 ± 10.84 b</td>
</tr>
<tr>
<td>Total OP</td>
<td>505.58 ± 22.28 a</td>
<td>507.43 ± 57.58 a</td>
<td>665.88 ± 60.09 b</td>
</tr>
<tr>
<td>Total P</td>
<td>828.03 ± 20.74 a</td>
<td>801.92 ± 55.11 a</td>
<td>942.01 ± 67.54 b</td>
</tr>
</tbody>
</table>

Note: Different letters along the row indicate significant differences between the means of the P fractions of the different vegetation types (Duncan’s multiple, *P* = 0.05)

Fig. 1. Percent contribution of different P fractions in total P content. (a) – proportion of organic P and inorganic P in total P; (b) – proportion of labile P and refractory P in total P; (c), (d) – proportion of different P fractions in labile P and refractory P respectively. ASM – alpine shrub-meadows, AS – alpine shrubs, SCF – subalpine coniferous forests.
When the total soil P was divided into labile P and refractory P, the amount of labile P was generally low and accounted for approximately 10% of the total P (Fig. 1b). Although the labile P was significantly higher in subalpine coniferous forests, no significant differences were observed in the refractory P concentrations of the different vegetation types (Table 2). The labile and refractory P pools were dominated by NaHCO$_3$–OP and NaOH–OP, respectively (Figs. 1c and 1d).

For these alpine soils, Resin–IP, NaHCO$_3$–OP, and labile P had significantly positive correlations with SOC and MB–P (Table 3). Both NaOH–IP and NaOH–OP had significantly positive correlations with Al and Fe (Table 3). The P fractions associated with the parent minerals (HCl–IP and cHCl–IP) had significantly positive correlations in terms of Ca contents and pH (Table 3). The total OP and the dominant OP fraction (NaOH–OP) had a significantly positive correlation with SOC, total N, and MBP (Table 3).

4. DISCUSSION AND CONCLUSION

4.1. Biogeochemical influences on alpine soil P fractions

Alpine soils (Inceptisols) are usually considered to exhibit low levels of weathering and microbial activity, where IP is the dominant fraction of soil P and parent materials control soil P cycling (Cross and Schlesinger 1995, Cassagne et al. 2000). However, in our study, OP was found to be the dominant fraction of the total P and labile P, which is similar to other findings in alpine regions (Beck and Elsenbeer 1999, Cassagne et al. 2000, Shiels and Sanford 2001, Litaor et al. 2005). Biological processes, especially P utilization and deposition in the topsoil by plants, seem to be more important to the P fractions distribution than the contribution of the parent material to the surface soil. Higher C:N ratios and low temperatures in cold alpine climates impede the mineralization ratio of OP, a fact that is also verified by an inhibition of phosphatase and microbial activity (Cassagne et al. 2000, Shiels and Sanford 2001, Johnson et al. 2003).

The distribution of IP fractions across the study site is similar to that in soil from the desert and polar areas (Cross and Schlesinger 2001, Bate et al. 2008). Surface soil contained large amounts of P fractions associated with the parent minerals (HCl–IP and cHCl–IP), indicating that the parent minerals also exert strong influences on P cycling (Cross and Schlesinger 2001).

4.2. Effects of vegetation type on soil P availability and fractions

Although biogeochemical cycles control soil P, soil–available P is influenced predomi-
nantly by biological processes and is mostly derived from soil organic matter – SOM (Wood et al. 1984, Cross and Schlesinger 1995, Thomas et al. 1999). Greater labile P concentrations found in subalpine coniferous forests are attributed to the greater SOM content in subalpine coniferous forest soils. These results are in agreement with the findings of Parker and Sanford (1999) and Shiels and Sanford (2001) about larger concentrations of labile P found in krummholz forest soil as opposed to the adjacent tundra soil. They suggested that these differences in plant-available fractions of soil P are due to the presence of the deep organic litter layer generated by trees. The litter layer can directly replenish labile IP and labile OP through the mineralization and mobilization of low molecular weight materials, respectively (Shiels and Sanford 2001). In addition, due to their rapid turnover, soil microbes are not only involved in mineralization but are also important in labile P pools themselves (Brookes et al. 1982, Hedley et al. 1982, Redel et al. 2008). As such, deeper litter layers in subalpine coniferous forests can also enhance MB–P concentrations (Table 1) by moderating fluctuations in soil temperature and moisture and providing a substrate for soil enzymes (Shiels and Sanford 2001, Lin et al. 2006).

The significantly positive correlation between total OP and SOC, indicating greater total OP concentrations in subalpine coniferous forests than in alpine shrubs and alpine shrub-meadows, is ascribed to greater amounts of organic matter input in forest ecosystems. As for the individual fractions of OP, the results indicate that the subalpine coniferous forest soil contains higher amounts of M in labile and moderately labile organic fractions (NaHCO₃–OP and NaOH–OP), whereas the alpine shrub-meadow soil contains larger amounts of stable OP (cHCl–OP). The apparent differences among the vegetation types in terms of SOM (soil OP) quality and quantity may help explain why more stable OP fractions exist in alpine shrub-meadows than in alpine shrubs or subalpine coniferous forests (Chen et al. 2008). Kammer et al. (2009) revealed that labile organic matter was greater and contained more available substrates for microorganism decomposition in forest ecosystems compared to the adjacent tundra soil. Pei et al. (2001) also found that soil OP obtained mainly from dead roots in alpine meadows is resistant to decomposition in frequent freeze-thaw conditions. Much of the NaOH–OP is stabilized by association with secondary Al and Fe minerals in the soil (Turner et al. 2005). For this reason, larger amounts of Al and Fe in subalpine coniferous forests compared to alpine shrubs and alpine shrub-meadows (Table 1) may help accumulate NaOH–OP (Cross and SchleConifers have been established to have the ability to dissolve P associated with Ca and parent minerals (e.g., apatite) to meet their P requirements (Condron et al. 1996, Johnson et al. 2003, Chen et al. 2008). Organic acids originating from the roots and ectomycorrhizae exudation in conifers can enhance the solubility of calcium phosphate, which can then increase soil P availability (Chen et al. 2004, Blum et al. 2002, Chen et al. 2008). The lower concentrations of HCl–IP and cHCl–IP in subalpine coniferous forests were accompanied by decreases in pH, unlike the case for alpine shrubs and alpine shrub-meadows (Table 1). These observations conform to the results of previous studies on tree species and adjacent alpine tundra (Parker and Sanford 1999, Shiels and Sanford 2001). The enhanced NaOH–IP concentrations found in subalpine coniferous forests are consistent with the findings of Chen et al. (2004) and Zhao et al. (2007). Their findings indicate that moderately labile IP (NaOH–IP) concentrations in surface soils in coniferous plantation forests are generally greater than those in adjacent grassland soil. Reduced soil pH in subalpine coniferous forests also improves OP mineralization by increasing the susceptibility of OP to enzyme hydrolysis (Adams and Pate 1992, George et al. 2002). Because soil IP was obtained mainly in the form of recalcitrant IP (HCl–IP and cHCl–IP) in the study region (Table 2), the reduction in soil pH and acceleration of OP formation seem to be an effective strategy in response to P deficiencies in subalpine coniferous forests.

### 4.3. Effects of vegetation type on soil OP mineralization

Mineralization of soil OP provides a large portion of the plant-available P in alpine soil...
ecosystems (Beck and Elsenbeek 1999, Cassagne et al. 2000). The C:OP ratio has been widely used to estimate the mineralization potential of soil OP (Duxbury et al. 1989). Across the study site, C:OP ratios were below 200 (Table 1). Thus, net mineralization readily occurs (Solomon et al. 2002, Wang et al. 2006). The mineralization of OP depends mainly on the intrinsic quality of SOM (soil OP) and microorganism decomposition (Stewart and Tiessen 1987, Zhao et al. 2007, Chen et al. 2008). As mentioned above, increasing recalcitrant SOM or soil OP input in alpine shrub-meadows and alpine shrubs can decrease the availability of substrates to microorganisms, unlike in subalpine coniferous forests. Larger MB–P concentrations in subalpine coniferous forests compared to those in alpine shrubs and alpine shrub-meadows also imply that easily more mineralizing OP (NaHCO$_3$–OP) may occur through lysis of microbial biomass in subalpine coniferous forests (Redel et al. 2008). In addition, the decrease in soil pH in subalpine coniferous forests may enhance the solubility of OP and increase its susceptibility to microbial attack (Adams and Pate 1992). Kammer et al. (2009) found that C and N mineralization decreases from forest to tundra soils. On the basis of the present results, we believe that soil OP mineralization may be lower in alpine shrubs and alpine shrub-meadows compared to subalpine coniferous forests, much like the trend for soil C and N.

4.4. Effects of vegetation types on soil P conservation and supply

Higher total P, as well as SOC and total N, in subalpine coniferous forests, compared to alpine shrubs and alpine shrub-meadows, implies that subalpine coniferous forests have higher soil nutrient-conserving abilities, which could be ascribed to high tree uptakes and efficient nutrient cycling through litterfall in forest ecosystems (Shiels and Sanford 2001, Johnson et al. 2003, Lin et al. 2006). Furthermore, if the forest floor P is taken into account, soil ecosystems in subalpine coniferous forests have significantly greater P-conserving abilities than alpine shrubs and alpine shrub-meadows (Shiels and Sanford 2001).

In fact, natural subalpine coniferous forests are the climax communities of alpine regions, ensuring self-sustained nutrient cycling and low losses; that is, soil P is replenished mainly by P recycling through litter-fall (Thomas et al. 1999, Lin et al. 2006). However, in alpine shrubs and alpine shrub-meadows, which have greater recalcitrant OP and lower MB–P, more and more P is accumulated in stable OP fractions rather than being returned to the ecosystem through decomposition. The low utility of resistant P fractions, such as the P associated with Ca, in alpine shrub-meadows and alpine shrubs can result in the accumulation of more recalcitrant IP fractions (HCl–IP and chCl–IP). Liu et al. (2004) hypothesized that soil fertilities degenerate and P-supplying abilities decrease in the forestlands compared to alpine meadows (shrub-lands) of this region. The results from our study confirm this hypothesis.

In conclusion, OP is the dominant fraction of soil P and the main source of available P in alpine soil near the timberline under study. The findings of this study clearly show that subalpine coniferous forests have greater amounts of labile P, moderately labile P, and total P, and take up more P associated with Ca. In contrast, alpine shrubs and alpine shrub-meadows produce greater stable OP and recalcitrant IP accumulation. Compared with alpine shrubs and alpine shrub-meadow, subalpine coniferous forest soil has better abilities to conserve P and enhance P availability. For areas in the region with high levels of deforestation, sustaining soil fertility by protecting the coniferous forests and litterfall is necessary.

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