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*Supplement of*

# Holocene fire regimes across the Altai-Sayan Mountains and adjacent plains: interaction with climate and vegetation types

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Supplement

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## S1. Charcoal influx-vegetation relationships at the selected sites

**In the southeast/west Altai Mountains within the steppe zone (Region A):**

**Tolbo Lake:** In the early Holocene, the charcoal influx was in the relatively high level with a average of 174.98 particles/$cm^2$/yr. Three peaks were observed at ~11.08, ~10.15, ~8.56 cal. kyr BP with the highest value of 757.07 particles/$cm^2$/yr (Fig. 4) (Hu et al., 2024). The relatively low charcoal influx was showed between ~8.2 and ~6 cal. kyr BP with a average of 59.86 particles/$cm^2$/yr. After ~6 cal. kyr BP, the charcoal influx shows an increasing trend with abnormal high value at ~1.20-~0.65 cal. kyr BP. Charcoal influx significantly increases with increasing *Pinus* ($p<0.001$) and forest cover ($p<0.001$), whereas that significantly increases with decreasing *Picea* abundance ($p=0.002$) and forest cover ($p<0.001$) (Table S2). *Betula* ($p=0.09$), *Larix* ($p=0.95$) abundance had insignificant effects on charcoal influx (Table 2, Fig. S1).

**Alahake Lake**: the charcoal influx was in the relatively low level with a average of 0.64 particles/$cm^2$/yr before ~1.44 cal. kyr BP, followed by an abrupt increase of charcoal influx at ~1.44-~1.02 cal. kyr BP with a relatively low value in the remaining interval (Li et al., 2021). In the past millennium, two peaks were showed at ~0.74-~0.67 cal. kyr BP and ~0.45-~0.37 cal. kyr BP (Fig. 2b). Only *Betula* ($p=0.04$) abundance had significant effects on charcoal influx. Charcoal influx insignificantly increases with *Abies* ($p=0.45$), *Larix* ($p=0.19$), *Picea* ($p=0.09$), *Pinus* ($p=0.089$), and forest cover ($p=0.26$) (Table 2, Fig. S1).

**Kuchuk Lake**: The obviously increased charcoal influx was occurred in the past 1500 years (Fig. 4b). The GAMs analysis reveals that *Abies* ($p=0.03$), *Betula* ($p<0.001$) and *Pinus sylvestris* ($p=0.01$) have significant positive relationship with Charcoal influx at Kuchuk Lake with the highest 25.5% explained deviance (Table 2, Fig. S2). Charcoal influx of Kuchuk Lake clearly reflected “human influence charcoal pulse” during last two millennium.

**In the west Siberian plain (Region B, n=4):**

**Rybnaya Mire**: Three high-value interval of charcoal influx occurred at ~7.45-~6.85 cal. kyr BP, ~6.35-~6.2 cal. kyr BP and ~4.5-~4.3 cal. kyr BP (Fig. 4c). The

GAMs analysis reveals that charcoal influx significantly decreases with increasing *Betula* (p=0.004, 18.4%) and forest cover (p=0.003, 16.2%), whereas that significantly decreases with decreasing *Picea* abundance (p=0.00, 44.5%) (Table 2, Fig. S2).

**Plotnikovo Mire**: two high-value interval of charcoal influx occurred at ~1.58-~0.98 cal. kyr BP and the past 350 years (Fig. 4c). The GAMs analysis reveals that only forest cover have significant positive relationship (p=0.004) with charcoal influx with the 39.70% deviance explanation (Table 2, Fig. S2). Other variables have no significant relationships with charcoal influx.

**Shchuchye Lake**: the highest charcoal influx (mean 4431.03 particles/cm$^2$/yr) was observed at ~12-~11.34 cal. kyr BP (Fig. 4c). The following interval (~11.34-~4.91 cal. kyr BP) was featured by the relatively low charcoal influx with an average of 787.31 particles/cm$^2$/yr. Increasing charcoal influx (mean 1481.92 particles/cm$^2$/yr) was observed in the past ~4900 years. The GAMs analysis reveals that all variables have significant relationships with Charcoal influx in Shchuchye Lake (Table 2, Fig. S3). The higher explained deviance for charcoal influx was presented in forest cover (57.4%), *Larix* (45.4%) and *Abies* (37.4%).

**Ulukh–Chayakh Mire**: the charcoal influx was relatively stable with four peaks at ~4.37-~4.21 cal. kyr BP, ~3.73-~2.88 cal. kyr BP, ~0.97-~0.92 cal. kyr BP and the past 300 years (Fig. 4c). Charcoal influx significantly increases with increasing *Betula* (p=0.01, 13.4%), whereas that significantly increases with decreasing *Pinus sylvestris* abundance (p=0.04, 10.3%) (Table 2, Fig. S3). Other variables (*Abies*, *Betula*, *Larix* *Picea*, *Pinus sibirica* and forest cover) has no significant relationships with Charcoal influx.

**In the northern Altai Mountains (Region C, n=4):**

**Chudnoye Mire**: the charcoal influx experienced a decreasing trend in the early and middle Holocene and turned to a quick increase (mean 1497.13 particles/cm$^2$/yr) in the late Holocene (Fig. 4c). The GAMs analysis reveals that only *Abies* pollen (p=0.14) and forest cover (p=0.17) have no relationship with charcoal influx (Table S2, Fig. S3). *Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* have significant relationships with charcoal influx. The high explained deviance for charcoal influx was presented in *Picea* (30.3%) and *Betula* (23.5%).

**Tundra Mire**: the charcoal influx decreased from 437.97 to 66.42 particles/$cm^2$/yr at ~7.28-~4.41 cal. kyr BP and increased to 1056.34 particles/$cm^2$/yr at ~4.41-~2 cal. kyr BP. The charcoal influx experienced a slow decrease at ~2-~1.65 cal. kyr BP, a quick increase at ~1.65-~0.88 cal. kyr BP with the highest value (3177.54 particles/$cm^2$/yr) at ~1.42-~1.32 cal. kyr BP and again a slow decrease in the remaining interval (Fig. 4c). The GAMs analysis reveals that only *Larix* pollen have significant positive relationship with charcoal influx with the 22.70% deviance explanation (Table 2, Fig. S4). Other variables (*Abies*, *Betula*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) has no significant relationships with charcoal influx.

**Mokhovoe Bog**: the charcoal influx in the Holocene interval can be divided into three parts: a slow decrease in the early Holocene, an abrupt increase at ~8.2 cal. kyr BP followed by a decrease at ~8.2-~6 cal. kyr BP. A quick increase of charcoal influx was also occurred at ~5.5-~4.2 cal. kyr BP with a following decreasing trend in the remaining interval. Six peaks of charcoal influx were showed at ~8.30, ~8.07, ~5.40, ~4.81, ~4 and ~1.42 cal. kyr BP (Fig. 4c). The GAMs analysis reveals that only *Picea* pollen (p=0.02) have significant relationship with charcoal influx at Mokhovoe Bog with 11.9% explained deviance (Table 2, Fig. S4).

**Kuatang Lake**: the charcoal influx kept a relatively low level with an average of 236.26 particles/$cm^2$/yr between ~5.87 and ~3.73 cal. kyr BP (Fig. 4c). The following interval was featured by the relatively high level with an average of 983.01 particles/$cm^2$/yr at ~3.73-~1.78 cal. kyr BP. The charcoal influx turned to the lower level in the next 1200 years and again increased in the past 500 years. The GAMs analysis reveals that charcoal influx significantly increases with increasing *Betula* (p=0.00), *Pinus sibirica* (p=0.05), *Pinus sylvestris* (p=0.02) pollen and forest cover percentage (p=0.003), whereas that significantly increases with decreasing *Abies* (p=0.04). *Larix* and *Picea* have no significant relationship with charcoal influx (Table 2, Fig. S4).

**The central Altai Mountains within the forest zone (Region D, n=3):**

**Dzhangyskol Lake**: there are two high-value interval of charcoal influx at ~12-~10 cal. kyr BP (3.88 particles/cm$^2$/yr) and the last millennium (8.10 particles/cm$^2$/yr) (Fig. 4e). The remaining interval (~10-~1 cal. kyr BP) was characterized by a low value (1.08 particles/cm$^2$/yr) with a slight increasing trend of charcoal influx. The GAMs analysis reveals that all variables have no significant relationships with charcoal influx (Table 2, Fig. S5). *Pinus sylvestris* has the largest deviance explanation (22.80%) for charcoal influx with a positive relationship.

**Uzunkol Lake**: the charcoal influx was lower with an average of 46.16 particles/cm$^2$/yr before ~4.76 cal. kyr BP with an abnormally peak (531.78 particles/cm$^2$/yr) at ~9.18 cal. kyr BP (Fig. 4e). Between ~4.76 and ~1.25 cal. kyr BP, the charcoal influx obviously increased with an average of 93.13 particles/cm$^2$/yr. The maximum charcoal influx (mean 244.67 particles/cm$^2$/yr) was recorded in the past ~1.25 cal. kyr BP with a quick decreasing trend. The GAMs analysis reveals that charcoal influx significantly increases with increasing *Abies* (p=0.02) and *Pinus sylvestris* (p=0.02) percentage, whereas that significantly increases with decreasing *Betula* (p=0.008), *Picea* (p=0.00) and *Larix* (p=0.00). *Pinus sibirica* and forest cover has no significant relationships with charcoal influx (Table 2, Fig. S5).

**Kendegelukol Lake**: the charcoal influx was lower (mean 16.23 particles/cm$^2$/yr) at ~12-~10 cal. kyr BP and turns the higher level in the remaining interval with two peaks at ~4.16-~3.65 cal. kyr BP (mean 349.79 particles/cm$^2$/yr) and ~1.45-~1.30 cal. kyr BP (mean 199.35 particles/cm$^2$/yr) (Fig. 4e). The GAMs analysis reveals that charcoal influx significantly increases with increasing *Abies* (p=0.04), *Betula* (p=0.02), *Pinus sylvestris* (p=0.00) pollen with >40% explained deviance. Other variables (*Larix, Picea*, *Pinus sibirica* and forest cover) has no significant relationships with charcoal influx (Table S2, Fig. S5).

**The central Altai Mountains above the forest limit (Region E, n=3):**

**Akkol Lake**: the charcoal influx can be divided into four intervals: a lower interval at ~12-~10 cal. kyr BP, the maximum interval at ~10-~5 cal. kyr BP, a lowing interval at ~5-~2 cal. kyr BP and a slight increasing interval in the past two millennium (Fig. 4f). The GAMs analysis reveals that charcoal influx significantly decreases with decreasing *Picea* (p=0.00), *Pinus sylvestris* (p=0.002) and forest cover (p=0.00) (Table 2). Other variables (*Abies*, *Betula*, *Larix*, *Pinus sibirica*) has no significant relationships with charcoal influx (Table 2, Fig. S6).

**Tashkol Lake**: the highest charcoal influx was showed at ~12-~10 cal. kyr BP. The increasing trend of charcoal influx was showed before ~5.5 cal. kyr BP, followed by a decreasing trend in the remaining interval (Fig. 4f). The GAMs analysis reveals that charcoal influx significantly decreases with decreasing *Picea* pollen (p=0.04) with 40.7% explained deviance (Table S2). The second higher explained deviance (17%) for charcoal influx was forest cover, but no significance was recorded in Tashkol Lake. The explained deviance of other variables (*Abies*, *Betula*, *Larix, Pinus sibirica*, *Pinus sylvestris* and forest cover) are less than 5% (Table S2, Fig. S6).

**Grusha Lake**: the charcoal influx show a decreasing trend from 48.64 to 7.77 particles/$cm^2$/yr since late glacial to ~1.6 cal. kyr BP and followed by a slow increase in the remaining interval (Fig. 4f). The GAMs analysis reveals that charcoal influx significantly decreases with decreasing *Larix* (p=0.02), *Picea* (p=0.05) and forest cover (p=0.00) with the largest deviance explanation (71.10%) (Table S2). Other variables in Akkol Lake (*Abies*, *Betula*, *Pinus sibirica* and *Pinus sylvestris*) has no significant relationships with charcoal influx (Table S2, Fig. S6).

**The Western Sayan Mountains (Region F, n=3):**

**Bezrybnoye Mire (within mountain forest upper limit)**: the charcoal influx show a quick increase from 449.95 to 2691.87 particles/$cm^2$/yr at ~4-~5 cal. kyr BP and experienced a quick decrease in the late Holocene (Fig. 4g). The GAMs analysis reveals that all variables has no significant relationships with charcoal influx (Table S2, Fig. S7). *Pinus sylvestris* had the largest deviance explanation (28.10%) for charcoal influx with a negative relationship.

**Buibinskoye Mire (within mountain forest upper limit)**: the charcoal influx show a quick increase from 1581.52 to 10765.67 particles/$cm^2$/yr in the early Holocene and experienced a quick decrease from 10765.67 to 210.43 particles/$cm^2$/yr in the middle and late Holocene (Fig. 4g). The GAMs analysis reveals that charcoal influx significantly decreases with decreasing *Abies* (p=0.004) pollen percentage

(Table 2). Other variables (*Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) has no significant relationships with charcoal influx (Table S2, Fig. S7).

**Lugovoe Mire (within mountain forest)**: the charcoal influx significantly decreased from 1338.64 to 19.07 particles/$cm^2$/yr at ~7.7-~1.18 cal. kyr BP and turned to a quick increase to 837.66 particles/$cm^2$/yr in the remaining interval (Fig. 4g). The GAMs analysis reveals charcoal influx significantly decreases with decreasing *Abies* (p=0.02) and *Larix* (p=0.008) pollen percentage, whereas that significantly decreases with increasing *Pinus sylvestris* pollen (p=0.01) (Table S2). Other variables (*Betula*, *Picea*, *Pinus sibirica*, forest density and forest cover) has no significant relationships with charcoal influx (Table S2, Fig. S7).

**The Khangai Mountains (Region G, n=3):**

**Olgi Lake**: the charcoal influx was relatively low in the whole interval with an average of 9.19 particles/$cm^2$/yr and one peak (88.28 particles/$cm^2$/yr) forest cover appeared at ~3.5-~3.1 cal. kyr BP (Fig. 4h). Charcoal influx significantly correlates with *Betula* (p=0.02), *Larix* (p=0.03), *Picea* (p=0.003), *Pinus* (p=0.00) and forest cover (p=0.00) (Table 2, Fig. S8).

**Shireet Naiman Nuur**: the charcoal influx experienced a decreasing trend in the past 7600 years with two peaks at ~6.9-~6.7 cal. kyr BP and ~3.7-~3.3 cal. kyr BP (Fig. 4h). The GAMs analysis reveals that all variables has significant relationships with Charcoal influx (Table 2, Fig. S8). Forest cover (37.4%), *Pinus sibirica* (27.5%) and *Betula* (20.7%) had the larger deviance explanation for charcoal influx with a positive relationship.

**Ugii Nuur**: the charcoal influx had two peaks at ~8.46-~7.49 cal. kyr BP and ~2.44-~2.12 cal. kyr BP (Fig. 4h). The value of charcoal influx in the latter period (mean 1644.66 particles/$cm^2$/yr) is totally higher than that in the former interval (mean 689.61 particles/$cm^2$/yr). The GAMs analysis reveals *Larix* (p=0.00), *Pinus sibirica* (p=0.00) and forest cover (p=0.00) has significant relationships with charcoal influx (Table S2, Fig. S8), while *Betula* (p=0.06) and *Picea* (p=0.67) has insignificant relationships with charcoal influx.

# Figures S1 to S8

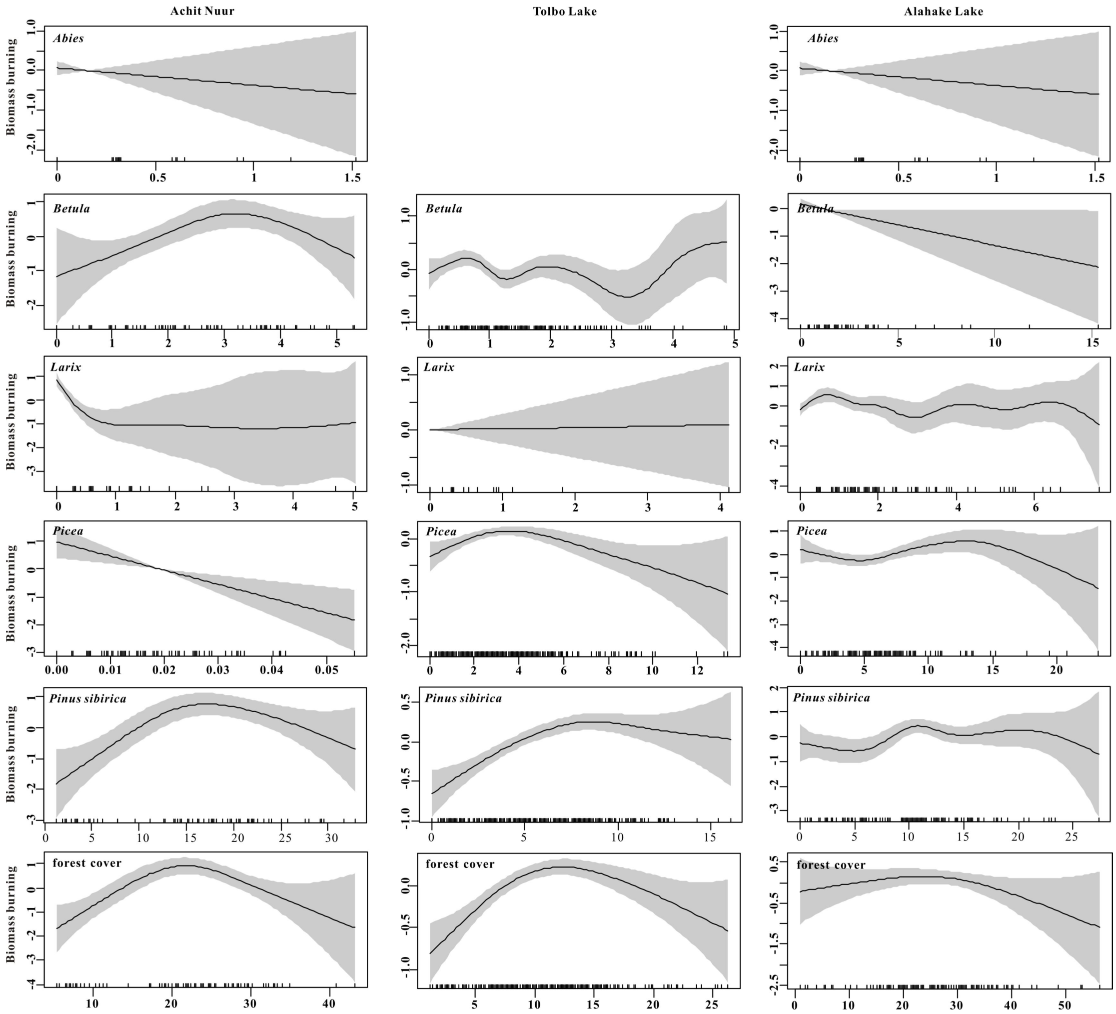


**Fig. S1.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies, Betula*, *Larix*, *Picea*, *Pinus sibirica* and forest cover) in Achit Nuur, Tolbo Lake and Alahake Lake. Pointwise confidence intervals (95%) are indicated by the gray bands.

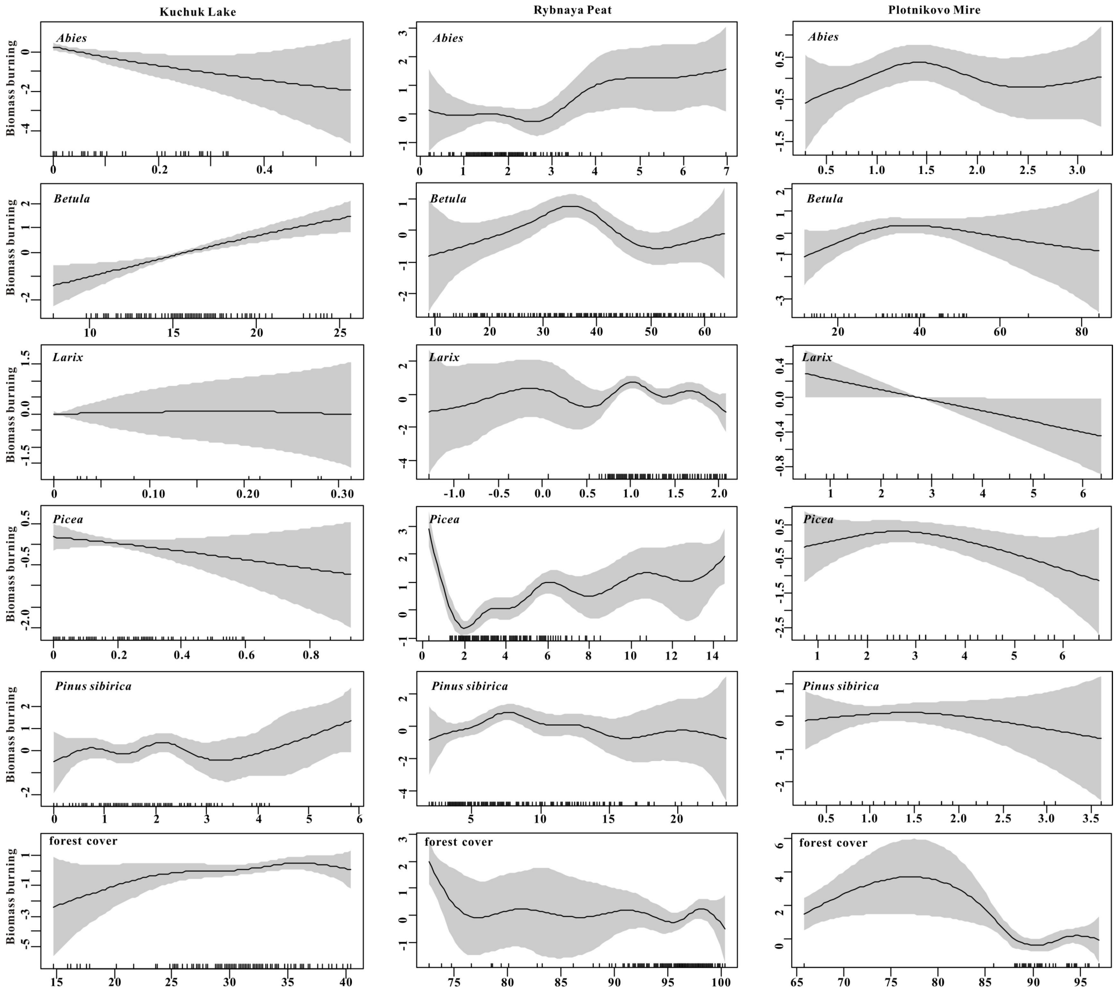


**Fig. S2.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies, Betula*, *Larix*, *Picea*, *Pinus sibirica* and forest cover) in Kuchuk Lake, Rybnaya Mire and Plotnikovo Mire. Pointwise confidence intervals (95%) are indicated by the gray bands.

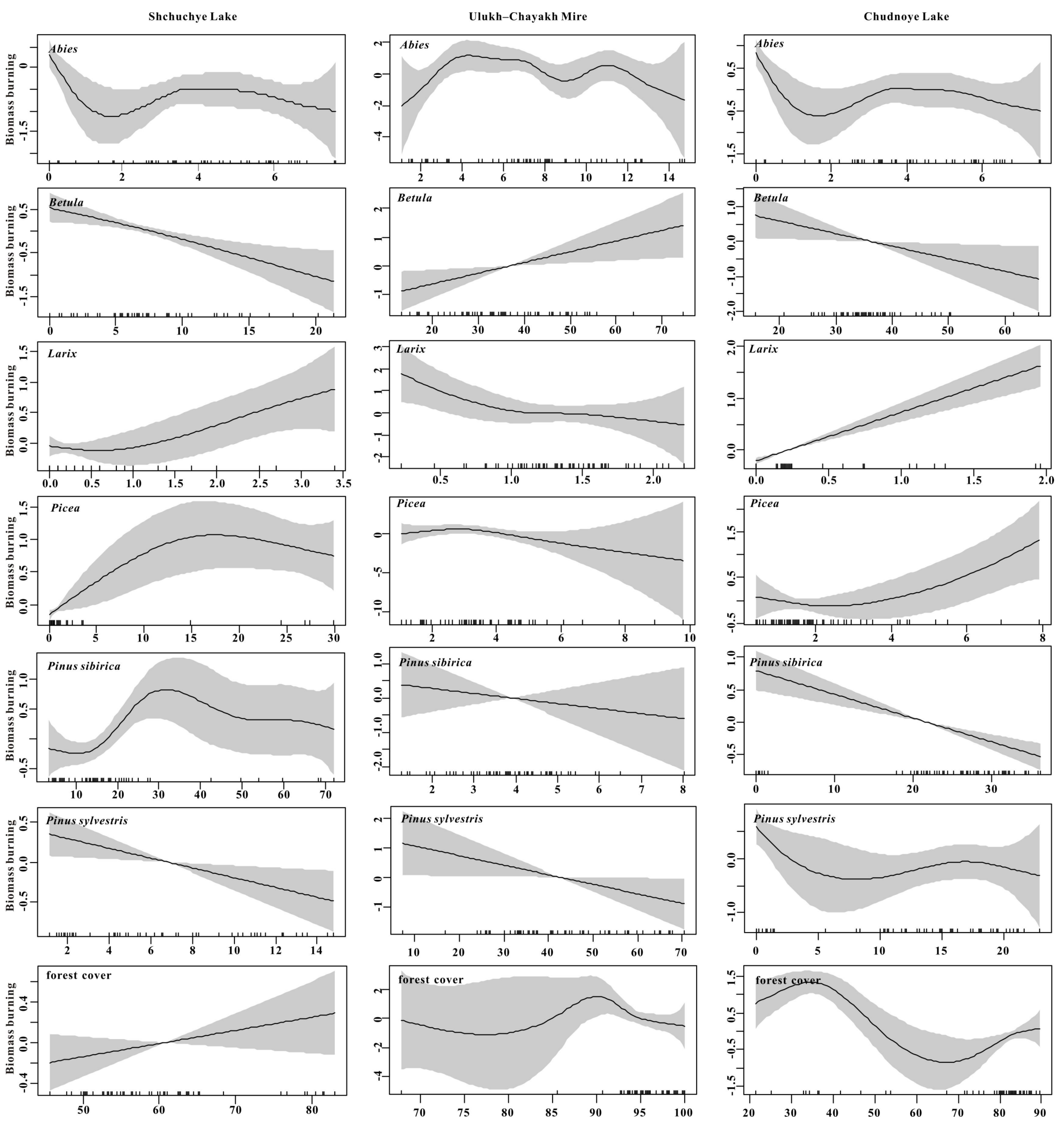


**Fig. S3.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies, Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) in Shchuchye Lake, Ulukh-Chayakh Mire and Chudnoye Mire. Pointwise confidence intervals (95%) are indicated by the gray bands.

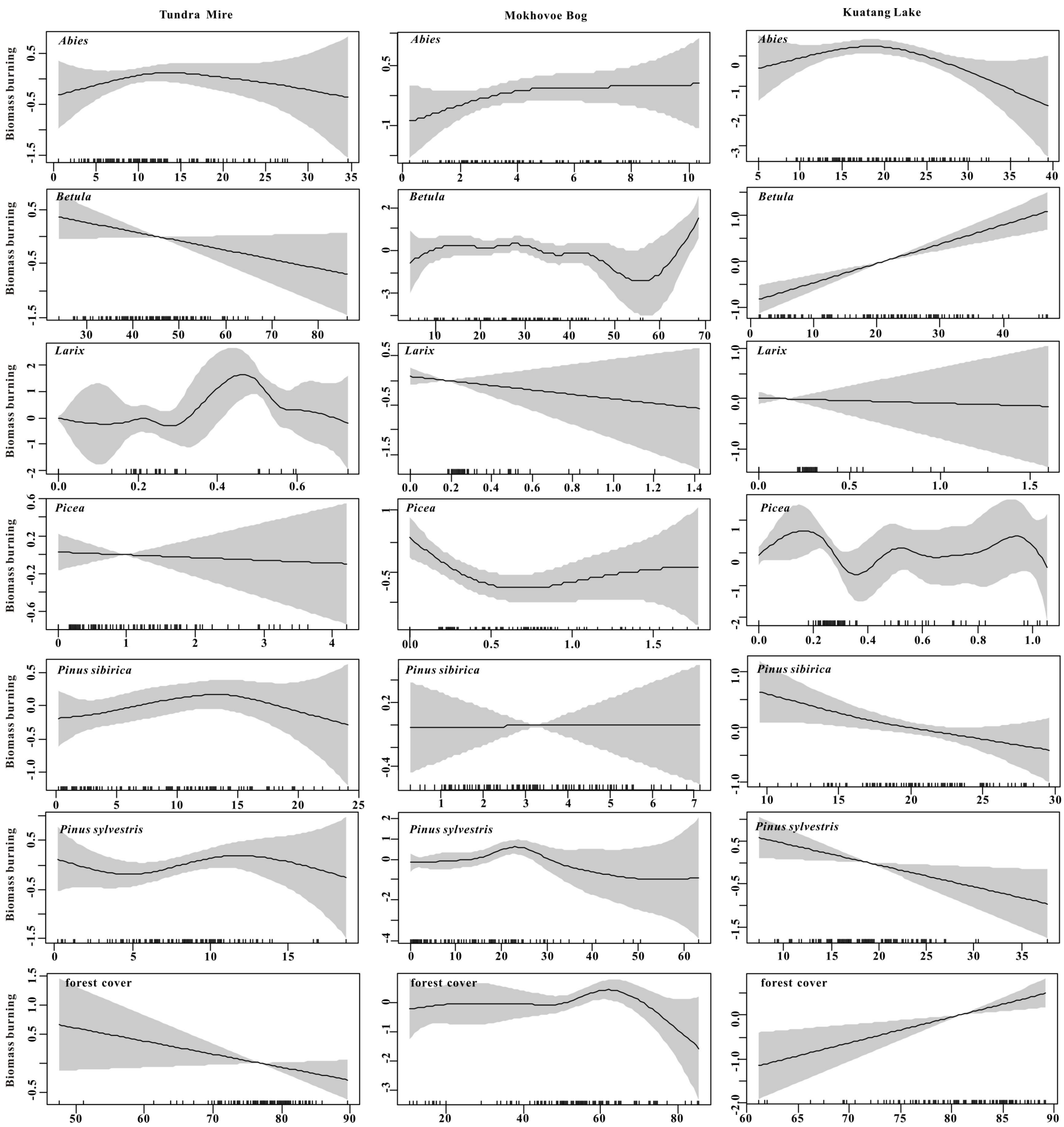


**Fig. S4.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies, Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) in Tundra Mire, Mokhovoe Bog and Kuatang Mire. Pointwise confidence intervals (95%) are indicated by the gray bands.

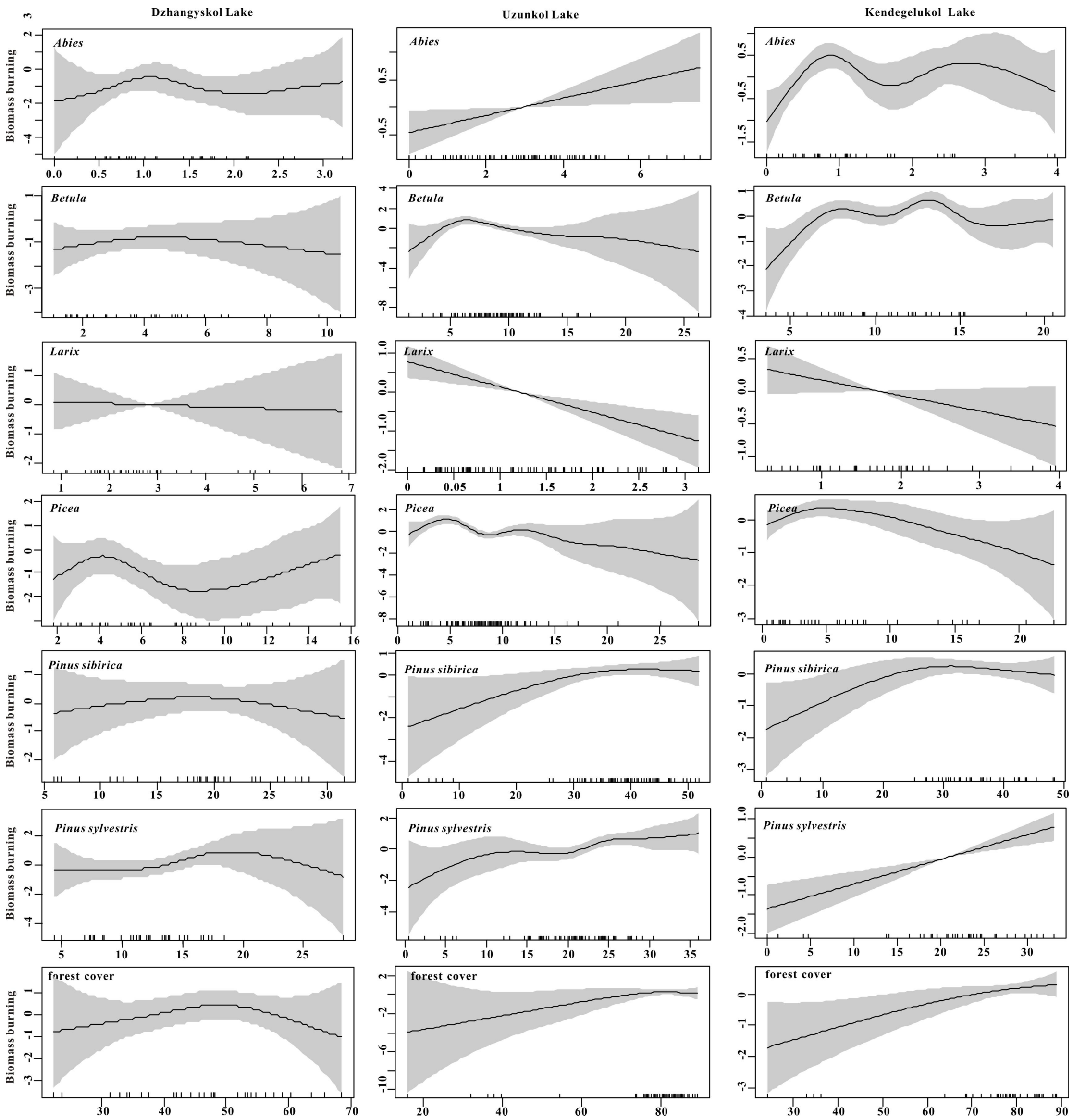


**Fig. S5.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies, Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) in Dzhangyskol Lake, Uzunkol Lake and Kendegelukol Lake. Pointwise confidence intervals (95%) are indicated by the gray bands.

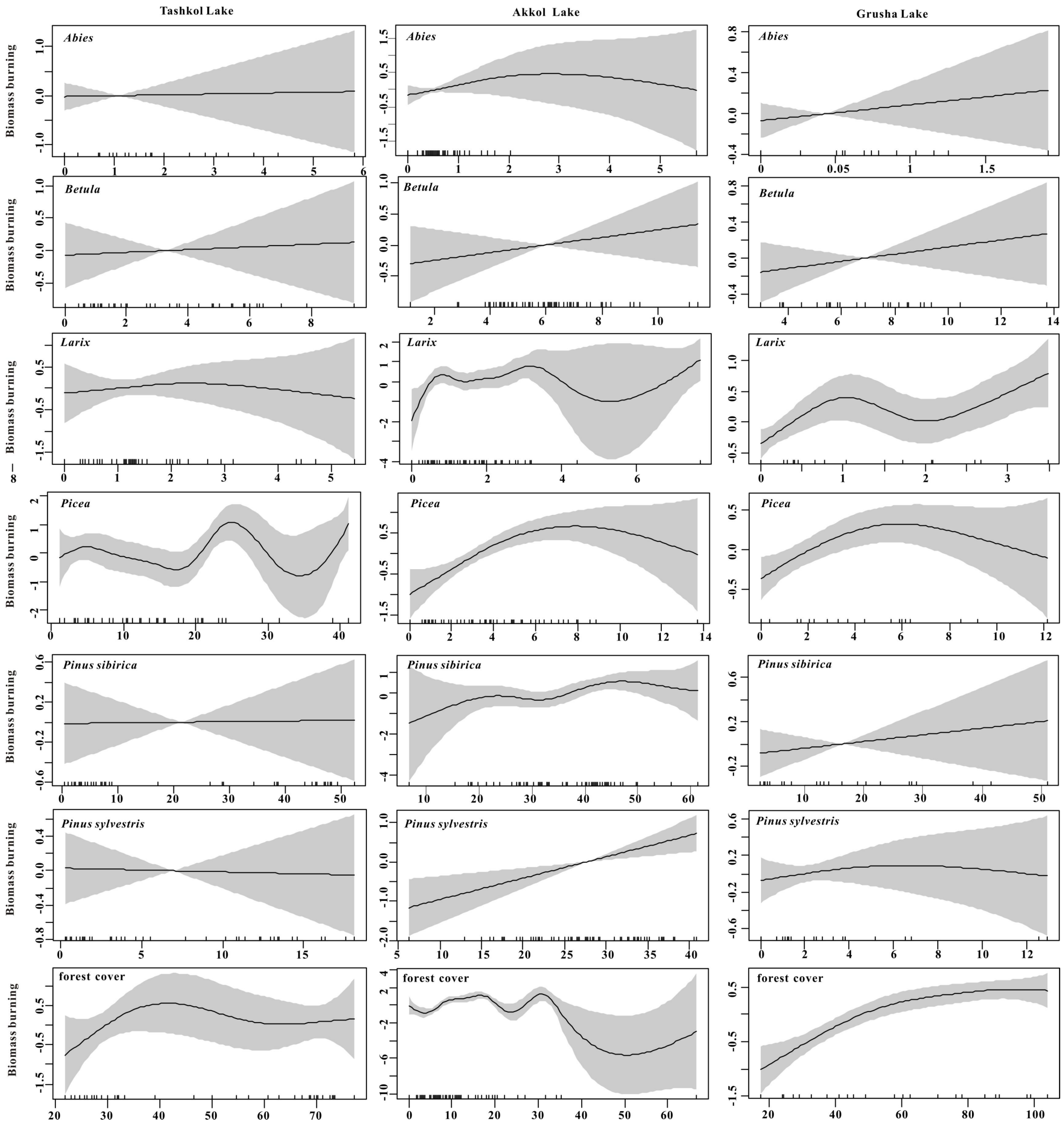


**Fig. S6.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies, Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) in Tashkol Lake, Akkol Lake and Grusha Lake. Pointwise confidence intervals (95%) are indicated by the gray bands.

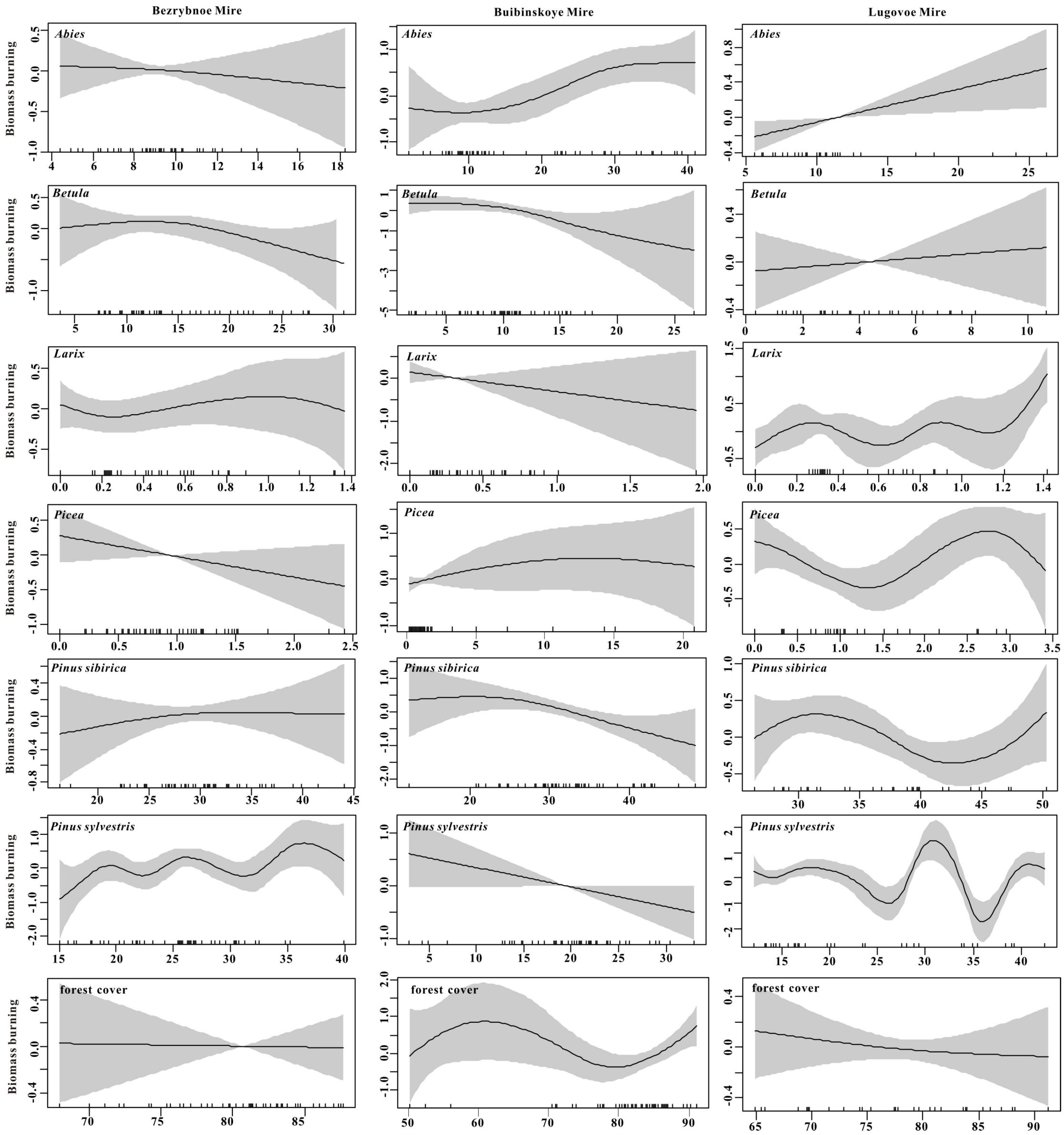


**Fig. S7.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies, Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) in Buibinskoye Mire, Bezrybnoye Mire and Lugovoe Peat. Pointwise confidence intervals (95%) are indicated by the gray bands.

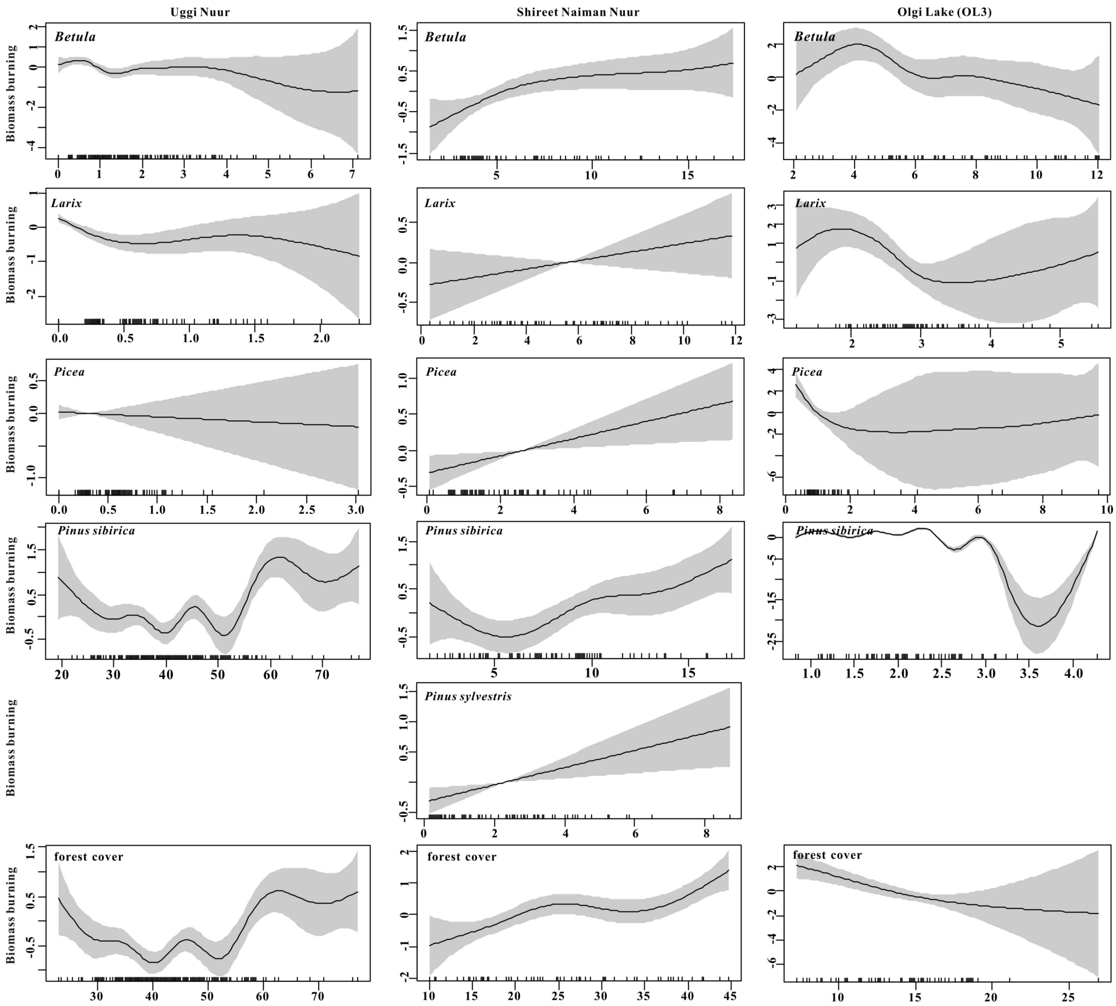


**Fig. S8.** Generalized Additive Models showing the relationship between charcoal influx (y-axis) and dominant drivers (*Abies*, *Betula*, *Larix*, *Picea*, *Pinus sibirica*, *Pinus sylvestris* and forest cover) in Olgi Lake(OL3), Shireet Naiman Nuur and Uggi Nuur. Pointwise confidence intervals (95%) are indicated by the gray bands.

**Table S1** Dating results of Achit Nuur (Sun et al., 2013).

| LAB code | Depth (cm) | Dated Material | $\delta^{13}C$ (‰) | $^{14}C$ age (yr BP) | Error (yr BP) |
|---|---|---|---|---|---|
| AA94349 | 0-2 | Bulk sediment | -13.3 | 2099 | 35 |
| AA94350 | 30-31 | Bulk sediment | -13 | 2673 | 38 |
| AA94351 | 51-52 | Bulk sediment | -11.7 | 2981 | 39 |
| AA94352 | 73-74 | Mollusc | -8.3 | 4421 | 38 |
| AA94353 | 85-86 | Bulk sediment | -9 | 5497 | 40 |
| AA94354 | 105-106 | Bulk sediment | -7.9 | 6717 | 61 |
| AA94355 | 127-128 | Root | -7.9 | 9971 | 52 |
| AA94356 | 148-149 | Bulk sediment | -7.6 | 11300 | 62 |
| AA94357 | 165-167 | Bulk sediment | -6.9 | 11796 | 92 |
| AA94358 | 190-191 | Bulk sediment | -3.7 | 18600 | 110 |