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Carbon stock in Korean larch plantations along a chronosequence in the Lesser Khingan Mountains, China

Wei MA • Yan-hong LIU • Yu-jun SUN • Jason Grabosky

Abstract: Carbon (C) dynamics are central to understanding ecosystem restoration effects within the context of Grain for Green Project (GGP). GGP stared in China since 2003 to improve the environment. Despite its importance, how total forest ecosystem C stock (FECS) develops following land-use changes from cropland to plantation is poorly understood, in particular the relationship of C allocation to pools. We quantified C pools in a chronosequence ranging from 0 to 48 years, using complete above- and below-ground harvests based on detailed field inventory. Stands were chosen along a succession sequence in managed plantations of Korean larch (*Larix olgensis* Henry.), a native planting species in the Lesser Khingan Mountains, Northeast of China. The FECS of Korean larch plantation (KLP) were dynamic across stand development, changing from 88.2 Mg·ha^{-1} at cropland, to 183.9 Mg·ha^{-1} as an average of forest C from 7- through 48-year-old plantation. In a 48-year-old mature KLP, vegetation comprises 48.63% of FECS and accounts for 67.66% of annual net C increment (ANCI). Soil is responsible for 38.19% and 13.53% of those, and with the remainders of 13.18% and 18.81% in down woody materials. Based on comparisons of our estimate to those of others, we conclude that afforestation of Korean larch plantation is a valid approach to sequester carbon.

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Introduction

Recent studies on global carbon (C) cycle suggest that land sinks account for 30% of total anthropogenic C emissions from 2000 to 2006 (Canadell et al. 2007). The FAO (2010) declared that C storage in terrestrial vegetation exceeds 650 Pg for the period 1990 to 2010 and continues to be part of the active discussion regarding greenhouse gas emissions (GHGs) and afforestation-reduction commitments (UNFCCC 2011a). Forests have a higher C density than other types of ecosystems (Silver et al. 2004; Pibumrung et al. 2008) and are estimated to contain more than 56% of terrestrial C (Bonan 2008). Their management therefore could play an important role in reducing atmospheric CO_2 (Johnson and Kern 2003; Stinson et al. 2011). Widespread interest in terrestrial C management may change the dynamics of current land use by influencing the relative importance of specific management objectives (Lal R 1999; Feng et al. 2006).

Goodale et al. (2002) summarized data from the northern hemisphere and concluded that boreal forests sequester about 0.6–0.7 Pg C year^{-1}, allocated as 0.25 Pg C of vegetation biomass, 0.11 Pg C of dead materials, 0.13 Pg C of soil, and 0.08 Pg C of wood product. Zheng et al. (2011) suggested disturbances from nature and human activities reduced 36% of forest C, mainly determined by harvest (63%), land-use change (33%), and fire suppression (4%). A relatively large proportion of the reduction was due to land-use change in the conversion of forest into agricultural land (Erb 2004). Smith and Heath (2008) presumed that 80% of the aboveground forest C would be lost during a conversion to non-forested land use.

Carbon may be recaptured through afforestation projects, which would increase aboveground biomass and replenishing the soil C pool (Guo and Gifford 2002; Pibumrung et al. 2008; Tobias et al. 2010). With that understanding, the Grain for Green Project (GGP), the largest afforestation program in China, en-

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ables the transition of lands from agricultural use as a proposed method to restore and rebuild the degraded ecosystems as farmland land (Wu et al. 2008; Wang et al. 2010a).

However, it is important to recognize that it can take decades to achieve the original level of carbon stock (CS) after land-use changes. Because GGP is occurring on a large scale and will last for decades, it is important to monitor and assess the development of newly established forests. As various studies have reported, C dynamics are central to understanding ecosystem-restoration efforts; not only in the context of GGP, but also as part of solving the serious problem of global warming (Chastain et al. 2006; Woodbury et al. 2007; Meelis et al. 2009).

Estimating C allocation to sectors or pools over a long time scale is challenging because forest C should be based on both initial and continuous assessments of biomass extraction and be multiplied by the appropriate factor as carbon concentration. Long-term inventories are hard to keep consistent, comparable, and accurate for forest heterogeneity, natural factors, and human activities (Magnani et al. 2007; Stinson et al. 2011).

Due to such challenges, the research record within major forest types with regard to carbon concentration (c) is still rudimentary, and precise data on c are scant (Didier and Frédéric 2006; Tolunay 2009; Zhang and Wang 2009). High degrees of uncertainty are associated with most available estimates (Grace 2004; Bradford et al. 2009). In many present studies, C in forest ecosystems addresses only the aboveground tree and aspects of soil, but lacks an absolute estimate of belowground and understory biomass (Pregitzer 2003; Giardina et al. 2005; King et al. 2007). An additional limitation, the estimation of biomass that has been removed is necessary to trace its release or continued capture as C because it is also based on the content and productivity of the forest (Houghton 2005; Heath et al. 2011). Furthermore, less experimental evidence is available on the effect of forest practices, such as thinning, on the C pools (Smith and Heath 2002; Birdsey and Lewis 2003; IPCC 2006).

The goal of this study is to describe and compare the dynamics of net CS of Korean larch (*Larix olgensis* Henry.) forest ecosystem, as an afforestation transition from farmland use, along a chronosequence. Korean larch is regarded as a commercially important planting species in northeast China; thus Korean larch plantations (KLP) are representative of a large part of the Lesser Khingan Mountains and the region beyond. Stand-level inventories were based on forest inventory analysis (FIA) fixed-radius plots. The conventional biomass-carbon method was employed, using complete above- and below-ground harvests with a chronosequence approach.

We developed land-based estimates of CS in specific subsets of the total forest ecosystem. Highly detailed, species- and region-specific conversion factors as c for CS have been developed for refined estimates of FECS. Analysis of ongoing reporting for these plantations indicates that spatial identification of C sinks as well as explicitly estimating growth and forest practices for their contribution to forest C can provide information to managers for altering or creating management plans (Brown 2002; Oscar et al. 2004).

Materials and methods

The chronosequence

Our study was carried out at the Dongzhelenghe forest farm (46°31'–46°49' N; 128°55'–129°15' E), which represents the typical forest types and landscape of the Lesser Khingan Mountains. This area is classified in temperate mixed broadleaf-conifer forest region based on the system of Chinese national vegetation regionalization (Cao and Li 2007). A large proportion of the original forest had been destroyed by industrial logging long ago, and was subsequently reclaimed for farming.

Since the mid-1960s, the corn, soybean, and abandoned fields which occurred beside or surrounded by the forest, had been taken back gradually for planting KLP. In order to study the CS dynamic in KLP after returning from cropland, we used a space-for-time substitution (Carolina and Belén 2005). To set a benchmark, we first choose two plots of cropland to estimate CS. Ten stands along a sequence in the managed KLP were sampled.

The chronosequence for both cropland and forests plots ranged in age from 0 to 48 years (Table 1). Elevations at all stands are similar, predominantly occurring on south-facing lower slopes with modest variation in slopes from 6° to 10°. Soils at all sites are sandy loams on hill land forms that are similar in depth. All stands were established with an initial planting density of 2883 trees·ha^{-1}, had been tended and thinned (intensity did not exceed 30%) at intervals of 8–10 years, and the stand tree densities necessarily declined over time. For each experiment stand, two plots were assigned simultaneously in the summer of 2009, and the mean value used for data analysis is shown in Table 1. Mean DBH (diameter at breast height) across all stands ranged from 3.0 to 27.4 cm, mean tree height ranged from 3.0 to 29.2 m, and stand volume ranged from 3.917 to 283.712 m^3·ha^{-1}. In current stands, similar site condition and similar management practices reflected that stand-to-stand variation was modest. Therefore, we can assume that the ecological dynamics of forest growth and CS accumulation followed the same pattern.

Field measurement and sampling treatment

In our study, the CS of cropland was based on soil C measures and sampling of crops as the benchmark surrogate for C status before the afforestation land use change. With slight modifications to the application of previous researches (Skog et al. 2004; Smith et al. 2006; Woodbury et al. 2007), FECS can be divided into seven distinct storage sectors: live trees, understory vegetation, snags, down dead wood (DDW, included slash pile and coarse woody debris), forest floor (included fine woody debris, litter and duff), soil, and removed wood. Specially, removed wood C refers to a portion of live tree C initially that is sequestered as logs and periodically removed out forest, but other residues remain on the site.

These sectors were included in three major pools, as vegetation (live biomass), dead woody materials (DWM, dead biomass)

and soil. Also, they can be roughly divided into two types of non-soil (vegetation & DWM) and soil. Fixed-radius plots were designed for use in FIA programs for forest surveys to obtained inventory data and original samples for biomass and CS (Bechtold and Patterson 2005; USDA Forest Service 2007). We em-

ployed small-scale and highly accurate surveys on sub-plots for trees and residual piles (RP), micro-plots for shrubs, quadrats for herbs and forest floor, and transects for fine woody debris (FWD) and coarse woody debris (CWD) within each plot (described below).

Table 1: Physical characteristics of the stands used in the study of C stock dynamic of Korean larch plantations along a chronosequence for cropland and stands 0–48 years of age in the Lesser Khingan Mountains of China.

Stand age (years)	Altitude (m)	Slope (°)	Aspect (°)	Slop position	Mean DBH (cm)	Mean height (m)	Volume ($m^3 \cdot ha^{-1}$)	Density (trees·ha^{-1})	Mortality (%)	Coverage
0	329	5	SW17	Bottom	na	na	na	na	na	na
7	300	9	SW60	Lower	3	3	3.917	1963	0.62	0.16
9	299	8	SW65	Lower	4.9	6.7	4.181	1947	0.67	0.14
15	308	7	SE62	Bottom	11.5	12.4	94.178	1623	0.88	0.65
19	296	7	SW30	Middle	12.7	13.9	137.017	1560	2.33	0.76
23	354	10	SW6	Bottom	15.2	15.8	143.796	1352	2.6	0.83
27	304	5	SE39	Lower	15.8	16	146.737	1014	3.83	0.8
33	376	6	SE15	Middle	16.1	16.3	169.487	936	5.83	0.75
37	383	6	SW58	Lower	16.6	17.2	240.464	783	4.72	0.73
41	309	9	SE75	Lower	27.4	26.3	253.478	576	2.78	0.63
48	312	10	SE69	Lower	29.2	28.4	283.712	520	2.53	0.57

Note: the age was from afforestation age. "na" denotes "not applicable", as no live trees were found at the cropland.

Vegetation

In sub-plots, all rooted individual trees were tagged and characterized by DBH, height, and crown width. The understory vegetation was surveyed in two categories for more efficient sampling: woody plants (vines, shrubs, bushes, and tree saplings) and herb layer plants (herbaceous plants, grasses). Plant species, numbers, and dimensions for woody plants (vines, shrubs, and tree saplings) were measured in micro-plots. Inside quadrats nested within each sub-plot, each individual tree (by species) was measured by height as well as the extent of the foliage along its widest dimension and perpendicular to herbaceous plants. Total vegetation cover and the average height of all plants were visually estimated for graminoid grasses (including corn and soybeans in cropland).

Vegetation biomass was determined by using complete above- and below-ground harvests, and/or applying allometric regressions. Based upon the results of the tally survey, two to three representative trees near the mean size from trees of each plot were destructively sampled for development of allometric regressions to estimate biomass across the chronosequence. A tree was divided into roots and shoots, and shoots were separated into foliage, live branches, and bole components. Seven to 30 individuals of each species were collected to represent the range of sizes common in understory vegetation plants, and they were separated into foliage, stem, and roots or simply aboveground and root components by species. After clipping down and root excavation, the harvested materials were separated and weighed. Between 500–1000 g of fresh material was randomly sampled from each tissue group in the dissected trees, and taken to the lab.

Down dead materials

DWM was distinguished for five decay classes (DC) as defined by FIA methods (Woodall et al. 2008; Woodall and Monleon 2008). Measurements included branch diameter at the point of transect intersection, total branch length, small and large end diameter, DC, and species, were collected for every CWD piece that intersected a sub-plot transect (USDA Forest Service 2005; Woodall and Williams 2005; Woodall and Monleon 2008). Dimensions (height, width, length) of ground coverage were measured. FWD was sampled with methods described in Woodall et al (2008), and FWD samples for determinations of volume and density were collected in each DC following methods described in Woodall and Monleon (2008) and Catharina et al. (2008). We assumed litter and duff resulted in homogeneous distribution. Tallies for each layer as weight and thickness were conducted on three 50×50 cm^2 quadrants located at the end of each CWD transect, and a fraction of composite samples were collected.

Soil

Data on soil was obtained from profile layers with the general approach described by John et al. (2008). Three 1 m deep profiles of the soil (including humus and mineral soil) adjacent to subplots were used for collecting samples with a soil core sampler (100 cm^3). Whole-plot blended batch sub-samples for soil density were dried for 24 hours at 105°C, and other sub-samples were air-dried for 48–72 hours before being processed for testing the physical and chemical characteristics.

Biomass estimation

After oven drying at 85°C for 24–48 hours to reach constant weight, dry weights of all non-soil samples were measured to determine the fresh mass to dry mass conversion factors (p) to apply toward respective components of the whole-sample field mass.

For living plants, raw data was initially graphed to provide a visual assessment of the relationships between foliage, branch, bark, stem, root biomass, and the independent variables. A summation for whole-tree biomass regression models was also developed. Least-square regression models were then developed for individual variables using curve forms. Estimates of these organs biomass were regressed against independent variables, and corresponding biomass allometric equations were developed (Table 2). Models were selected on the basis of the best combination of predictor significance, improvement of fit (R^2), and analysis of residuals. Additional equations—as research results from Chen and Zhu (1989)—were provided for estimating the biomass of other tree species in the stand.

Table 2: Parameters of the allometric equations used to predict tree-component biomass of Korean larch along a chronosequence for stands 7–48 years of age in Lesser Khingan Mountains of China.

Dependent variable	a	b	Mean square error	R^2	n
Total trees	0.8463(D^2H)	2.3533	0.0771	0.951	58
Total shoots	0.8562(D^2H)	2.2921	0.0769	0.953	58
Total roots	0.7871(D^2H)	1.4614	0.1207	0.875	19
Trunk	0.9448(D^2H)	2.2227	0.0784	0.96	58
Canopy	0.6928(D^2H)	1.5656	0.1337	0.869	58
Branches	2.152(D)	2.926	0.1263	0.872	58
Foliage	1.042(D^2)	2.2904	0.1425	0.7903	58

Note: Models had the form $\log(W) = a \log(X) + b$, W is biomass (kg), and X is variable in parentheses: D is DBH (m), D^2 is DBH^2 (m²), D^2H is $DBH^2 \times H$ (m³). Regression predictors were considered significant at $p \leq 0.05$.

Volumes of DDW and forest floor were estimated by diameter, length and thickness of samples for each respective DC. The measured volume per unit plot area data was combined with bulk density (BD, dry mass/ wet volume) measures to develop the DWM biomass estimator. For snags, volume was calculated as live tree, and taken as CWD for biomass. We computed the biomass of DWM (B_{DWM}) using a simple linear equation:

$$B_{DWM} = f \sum_{i=1}^{n} (BD_i V_i) \tag{1}$$

where n is the total number of individual DWM samples, f is the conversion factor for per-unit area values, BD_i is the bulk density (kg·m⁻³) of ith individual per decay class, V_i is cubic volume (m³) of ith individual.

The entire plot biomass was summarized from all categories,

and quantified as biomass density (Mg·ha⁻¹) after scaling from sample area to hectare. The average of plots in each stand was used as a standard value and defined as stand biomass. We chose this method to avoid analysis with skewed data.

Carbon concentration determination

Converting biomass in non-soil sectors to C was based on c, which represented the proportion of C in dry organic matter. To quantify biases in CS estimates, we determined species-specific c values for each collected tissue or component type in the forest plot. After biomass measurements, three oven-dry subsamples were finely ground and homogenized. The resulting powder was sent to for c determination. Powder subsamples of 50–60 mg were determinated by instantaneous combustion with a Multi CN Analyzer (ELEMENTAR Vario EL III, Germany), and c expressed as mg C mass per 100-mg dry mass (%). For QA/QC, every c power subsample was run in triplicate with an error rate of less than 0.01%, and recorded as the mean value c of tissue to eradicate any discrepancies. Weighted mean c (WMC) of biomass tissue or components were weighted by biomass, taking into account their architecture for plants (Bert and Danjon 2006; Tolunay 2009; Zhang and Wang 2009).

Carbon stock and change

To derive CS for all non-soil sectors, c was applied to biomass estimates in the plot, summed, and scaled to an area basis (Mg·ha⁻¹). For soil, we do not include relatively inert inorganic C in this study, but soil organic matter (SOM) in well-mixed oven dried samples of each individual soil layer was determined by employing a potassium dichromate volumetry technique (Man et al. 2010). We corrected the original SOM value for unreacted SOM by multiplying a fixed modification factor of 1.1. After that, SOM was converted to soil organic carbon (SOC) by multiplying c of 0.58 (the Van Benmmelen conversion factor). Thus, soil C stock (SCS, Mg·ha⁻¹) was calculated directly as:

$$SCS = \sum_{i=1}^{8} (SD_i \cdot Mc_i \cdot d_i) / 10 \tag{2}$$

where, SD_i (g·cm⁻³) was the soil density of the ith layer, Mc_i (g·kg⁻¹) was SOC, d_i (cm) was soil thickness of ith layer. Given the relatively small area of sample coverage and virtually no gravel (larger than 2-mm grain size) in the clayey loam soil samples, we ignored volume percentage of gravel.

Individual estimates for each C pool were aggregated into FECS (Mg·ha⁻¹) of all stands along the chronosequence. After that, the ANCI (Mg·ha⁻¹·a⁻¹) for the whole ecosystem can be determined by dividing stand age:

$$ANCI = (C_1 - C_2) / (t_1 - 0) \tag{3}$$

where, t_1 was the current stand age (and thus along the chronosequence), C_1 was FECS of stand at t_1, and C_2 was CS of cropland. The positive value for stock change indicates a net increase

in C over the time interval. Alternatively, a negative value would indicate a decrease within the time interval.

Results

Carbon concentrations

Mean tissue c across the Korean larch varied from 40.8% in fine roots to 49.9% in live branches (Table 3). Variations in c within organs across the chronosequence was low, with coefficients of variation (CV) ranging from 0.9% to 8.4%, and live branches and fine roots being the most variable. The WMC of Korean larch reached 48.8% in the crown, 47.6% in the bole, and 45.3% in the roots, which resulted in 47.6% at tree level. Compared to other species as Zhang et al (2010) described, this 47.6% c of Korean larch was smaller than the Amur cork-tree (55.1%), Korean pine (53.2%), Manchurian ash (52.9%), and Manchurian walnut (52.4%) by 5.3–7.5 percentage points, but close to Mongolian oak (47.6%), and slightly larger than Dahurian larch (46.9%), Mono maple (46.4%) and white birch (46.1%). The mean WMC of all tree species was 48.4%.

We figured out the WMC for the sectors: trees (48.4%) > shrubs (46.9%)> herbs (40.8%)> DWM (43.5%) > forest floor (36.8%), all which averaged to 45.9% at stand level.

Table 3: Carbon concentrations (%) of all organs from a chronosequence of Korean larch in Lesser Khingan Mountains of China.

Age (years)	Foliage	Live branch	Dead branch	Stem	Bark	Stump	Large root	Coarse root	Intermediate root	Fine root
7	52.3	48.6	50.3	49.2	50.8	50.9	na	na	45.3	43
9	51.9	47.8	50.6	48.6	49.8	47.5	na	na	47.5	41
15	50.6	49.5	48	50.6	49.7	49.5	na	47.2	41.9	39.8
19	51.8	47.4	48.3	49.3	48.8	48.6	46.2	48.2	50.4	47.8
23	51.5	48.7	47.5	47.8	48.1	46.2	44.3	46.5	46.6	42.7
27	50.5	46.3	49.7	48.6	47.6	47.7	45.1	45.4	46.7	43.1
33	49.4	47.6	47.7	46.7	48.4	45.6	43.2	47.4	44.5	38.5
37	48.6	47.4	46.9	47.6	46.6	46.9	46.7	46.5	42.4	40.9
41	49.6	47.4	47.6	47.7	47.3	47.3	43.1	42	47.2	37.5
48	48.7	46.6	46.4	48.8	46.4	44.1	43.6	45.9	45.6	40.3
Mean	49.9	47.5	47.8	48.2	47.5	46.5	44.5	45.7	45.8	40.8
CV	1.9	0.9	2	1.2	2.1	3.8	2.1	3.6	6.3	8.4

Note: "na" denotes "not applicable", as no large roots were found at 7-year-old stand.

Table 4: Comparison of C stocks and annual net carbon increment for each sector in cropland and Korean larch plantations.

Plantation ages (years)	Stock (%)							ANCI rate (%)						
	Live trees	Understory vegetation	Standing dead trees	Down dead wood	Forest floor	Soil	Removed wood	Live trees	Understory vegetation	Standing dead trees	Down dead wood	Forest floor	Soil	Removed wood
0	Na	4.18	Na	Na	Na	95.82	Na	Na	Na	Na	Na	Na	Na	Na
7	3.05	2.54	0.03	0.14	2.08	92.07	0.08	-428.06	233.69	-4.2	-20.3	-292.27	621.77	-10.63
9	9.97	2.03	0.05	0.28	2.94	84.68	0.04	123.94	-22.51	0.63	3.54	36.55	-42.7	0.54
15	27.93	0.79	0.21	1.68	3.86	62.59	2.93	86.57	-6.32	0.66	5.22	11.98	-7.19	9.08
19	38.58	0.63	0.48	1.87	3.75	53.72	0.97	91.56	-4.25	1.15	4.43	8.9	-4.09	2.3
23	36.24	0.76	0.53	3.63	3.77	52.07	3.01	77.1	-3.11	1.12	7.72	8.03	2.75	6.4
27	33.77	1	0.77	4.63	3.6	51.01	5.22	65.4	-1.98	1.48	8.97	6.98	9.04	10.1
33	38.56	1.07	1.07	6.67	4.18	46.75	1.7	64.34	-1.26	1.78	11.14	6.98	8.34	2.84
37	39.95	1.27	1.05	7.41	3.78	42.18	4.36	63.03	-0.42	1.66	11.69	5.97	11.19	6.88
41	40.82	1.85	0.93	8.36	3.5	36.71	7.83	58.98	0.81	1.34	12.08	5.06	10.42	11.31
48	41.75	1.98	0.97	8.56	3.65	38.19	4.9	59.62	1.04	1.38	12.22	5.21	13.53	7

Note: "na" denotes "not applicable", as no live trees were found at the cropland. "-" denotes negative sign, as indicates decrement of SOC from cropland.

Carbon stock

Tree CS typically increased in a double sigmoid curve across the chronosequence, from 2.670 Mg·ha^{-1} at the 7-year-old stand to 122.863 Mg·ha^{-1} at the 48-year-old stand (Fig. 1 a). The live tree CS ratio was low in the youngest stands, increased sharply to a sub-maximum at age 19, briefly suffered a modest drop, and then ascended asymptotically from 33 to 48 years of age (Table 4). There was a significant difference (Fig.1, p <0.05), in CS between the individual stands of different development stages. The value of C stored in removed wood did not have a marked effect on FECS in the early stages (years 0–19) (Fig. 1 b), but reached maximum (22.416 Mg·ha^{-1}) at 41-year-old stand, and was responsible for 7.83% over the entire chronosequence. The under-

story CS displayed a U-shaped curvilinear pattern (Fig. 1 c). Though it recovered gradually, the understory contained no more than 2.54% of FECS. CS dynamics of DDW and standing dead trees are generally similar with S-shaped curves (Fig. 1 d, e) of

the tree, while the forest floor rose in a linear fashion (Fig. 1 f). Total CS of DWM in the 48-year-old stand amounted to a sink of about 38.756 Mg·ha^{-1}.
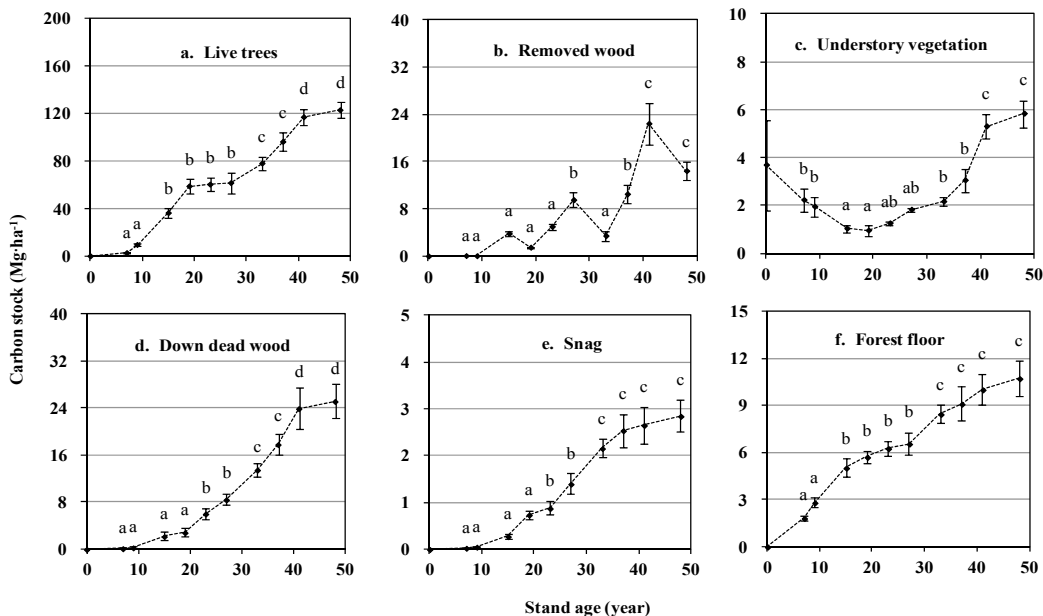

Fig. 1: Carbon stocks of sectors in farmland and Korean larch plantations along a chronosequence for cropland and forest stands 7–48 years of age. The process data were supported with X-axis gaps since relative regular stand age intervals. Error bars represent stand deviations of the means. The different small letters indicate significant difference by Duncan's multiple test (p =0.05).

Soil properties changed with increasing time from the transition of cropland to mature forest. Values of pH ranged from 6.89 to 6.23, generally decreasing over time. Soil BD decreased from 1.263 g cm^{-3} at cropland to 0.955 g cm^{-3} at the 27-year-old stand to less than 0.955 g cm^{-3} in the oldest forest plots. SOC increased from 16.39 g Kg^{-1} to 23.81 g Kg^{-1} as plot age increased (Fig. 2). In Fig. 2, it can be seen that SCS of 84.491 Mg·ha^{-1} at cropland was higher than that at the following forest stands until it was

approximately equal to the 23-year-old stand. Since then, SCS increased significantly and the highest CS of 112.363 Mg·ha^{-1} appeared at the 48-year-old stand. As measured across the increasing age of forest plots, the fraction of SCS decreased from 95.82% to 65.59% in the 19-year-old stand, remained constant at 53.72%–51.01% in the 23 to 33-year-old stands, and decreased from 46.75% to 38.19% in the 48-year-old stand.
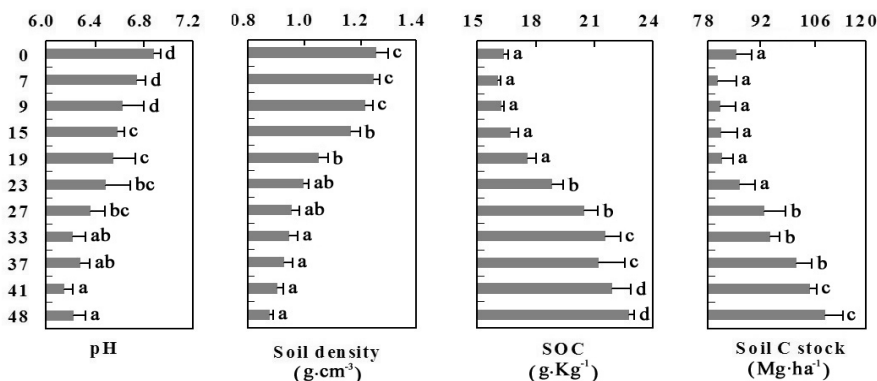

Fig. 2: The properties of soils in farmland and Korean larch plantations along a chronosequence of 7–48 years. Error bars represent stand deviations of the means. The different lower case letters within the same property indicated significantly different at p <0.05.

Carbon stocks from all different sectors were pooled to obtain a FECS combined within vegetation, soil, and DWM. Fig. 3

illustrates the time-trajectory of FECS follows a relative flat sigmoid pattern. At 87.553 Mg·ha^{-1}, the FECS of the 7-year-old

stand almost recovered to the original level of cropland with 88.177 Mg·ha⁻¹. In the 48-year-old stand, FECS reached a maximum of 294.192 Mg·ha⁻¹, which was 3.34 times than that in cropland. Specially, vegetation comprised 48.63% of FECS, SCS comprised 38.19%, and with the remainders of 13.18% in DWM. On average, soil was the biggest sink with 91.847 Mg·ha⁻¹, which was 1.37 times than 66.881 Mg·ha⁻¹ of vegetation and represents more than 49.96% percent of FECS.
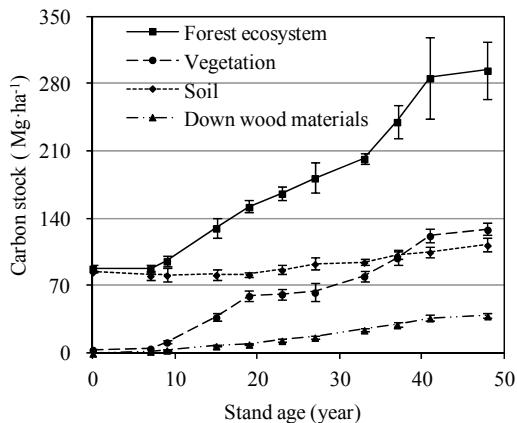

Fig. 3: Carbon stock growth curves by age of ecosystem and each layer of farmland and Korean larch plantations along a chronosequence 7–48 years of age.

Carbon accumulation

Shortly after the transition of land-use types, as seen in the 7-year-old stand, ANCI was below zero as -0.089 Mg·ha⁻¹·a⁻¹ due to the considerable SCS loss of 0.554 Mg·ha⁻¹·a⁻¹ (Fig. 4). In all of the older plots, ANCI was much higher because C was sequestered in the soil as well as in the non-soil pool. In this example, the 9-year-old stands were sequestering C at an ANCI of 0.913 Mg·ha⁻¹·a⁻¹. Latter, ANCI increased rapidly to 2.83 Mg·ha⁻¹·a⁻¹ in the 15-year-old stand, and then it increased slowly thereafter till 41-year-old stand of 4.847 Mg·ha⁻¹·a⁻¹ and 4.302 Mg·ha⁻¹·a⁻¹ in 48-year-old stand.
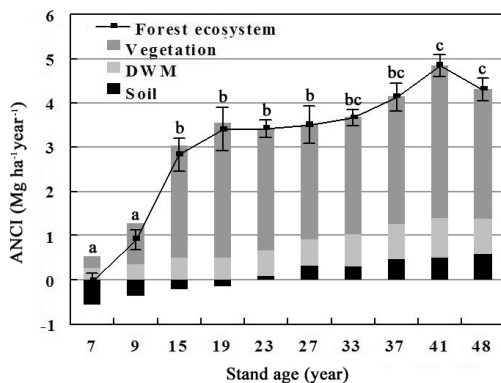

Fig. 4: Annual net carbon increment to farmland of Korean larch plantations along a chronosequence of 7–48 years.

C accumulated largely in vegetation, the proportion that held

in ecosystem total ANCI, was as high as 72.66 % of the total (see Table 4). Of the average net C accumulation in all stands, 18.26% is attributed to DWM on the average. For SOC, the accumulation increased from -0.554 Mg·ha⁻¹·a⁻¹ in the 7-year-old stand to 0.581 Mg·ha⁻¹·a⁻¹ in the 48-year-old stand, presumably through long-term humification processes.

Discussion

Estimate methodology

As such, the cumulative data set and approach reflects a viable and available method for developing stand-level CS estimates of forest ecosystems converted from cropland. The development of FIA plot investigation and the process of estimating biomass and c determination enabled us to accurately quantify FECS including the seven sectors. The stratified sampling of organs or tissues provided an excellent basis for capturing the variation in their dimensions or decay classes in the respective components. The excavation profile to 1 m deep allowed systemic soil sampling. Fresh mass to dry mass conversion factors and c were determined for all tissues or soil samples.

We found that models based on diameter and height provided a good fit to biomass for trees of all ages. Carbon stocks of DWM and soil were calculated based on measurements needed for available sampling formulas. In the case of two plots in the same stand age, values for all sectors in each stand were averaged to obtain one estimate per stand. Although many studies have included ecosystem-level assessments of C standing stocks (Mund et al. 2002; Albaugh et al. 2004), the current study provides precise accounting of all sectors and components rather than calculating one sector of C based on simply the roots versus shoot ratio or constant allocation coefficients. Simultaneously, we estimate the FECS dynamic contained in cropland, immature forest to mature forest, which permitted thorough CS dynamic.

Carbon concentration variation

Generally, the c values (i.e., 0.50 for wood, 0.45 for understory vegetation, 0.37 for DWM) are widely accepted as a constant factor for conversion of biomass to CS (IPCC 2006). Mass-based constant values may not be the best for accurate estimation of CS in forest. Variations between and within compartment in c had been considered in previous works (Tolunay 2009; Zhang and Wang 2009). Zhang et al. (2009) presumed that failing to account for the inter- and intra-specific variations in c would introduce a relative error of 6.7% to +7.2% in estimates of biomass CS from inventory data, of which >93% was attributed to ignoring the inter-specific variation in C. For the Korean larch forest ecosystem, the overestimation of C storage reached 4.89% if the usual 0.50, 0.45 and 0.37 conversion factors were used.

Carbon stock partitioning and trend over time

Croplands with degraded vegetation cover contained a lower

biomass density than the maximum potential value for the site and type of vegetation, established in this study as Korean larch plantations. Vegetation played a significant role as a primary producer in the KLP, which promoted the sustainable FECS growth along the chronosequence. Live standing trees amounted to 86.98% of the total amount of vegetation (which affected 34.99% of the FECS). The CS of thinning removals (as wood products in our study) accounts for a little more than 3.84% of all forest-related C stored by a forest. This is consistent with the statement that "wood products formed only a modest fraction of the total C stock" by other authors (Birdsey and Lewis 2003; Woodbury et al. 2007).

DWM provided corresponding responses to the vegetation changes, and the partitioning of it is proportional to levels at the time of thinning and added logging residue. Unlike reforestation, afforestation accounts for lower C densities of DDW and forest floor C in the initial years after forest establishment on non-forest post-cropland (Smith and Heath 2002). The DWM CS as we estimated represented a noteworthy percentage of the total ecosystem, approximately 9.82%, which was treated as an important transition layer between vegetation and soil (Jandl et al. 2007; Hudiburg et al. 2009).

It is clear that the conversion of agricultural land into KLP forest increased SCS by 32.99%, which is within the range of values from 18% to 53% associated with SCS after cropland was changed to plantation and secondary forest (Guo and Gifford 2002). Afforestation is likely to initially decrease SCS, as a result of disturbance during site preparation associated with erosion, loss of fertilizer regime, and root uptake (Jackson et al. 2002; Paul et al. 2002; Vesterdal et al. 2002; Susan et al. 2006). Undoubtedly, chemical and physical properties of soil used as indicators of soil strength and/or mechanical root impedance, can thus affect SCS (Drewry et al. 2008; Wang et al. 2010b).

Meanwhile, growing vegetation tend to maintain SCS level by continuously supplying C from root turnover (Jobbagy and Jackson 2002; Prévost 2004). Root CS specifically accounted for more than 4.67% of that in KLP ecosystem. According to our estimate, SCS is generally restored to the original stock after 20 years, and the soil C pool approached a new equilibrium, substantially higher than under cropland. Other chronosequence studies also support this theory (Romanyá et al. 2000; Zerva et al. 2005).

Given the slowing down of the development of trees, the associated slowing in total vegetation CS and the saturations of DWM and SCS, FECS will not expand quickly. We do wonder whether the increased growth rate can be sustained for an extended period during the over-mature stage, which has also been questioned by Adrien et al. (2006). Thus, we tend to identify the trajectory of FECS as a sigmoid pattern (Fig. 2).

Comparison with other forests

Our observed sequence of living tree biomass in KLP is generally consistent with that in the nearby Changbai Mountains (Wang et al. 2010a), higher than *Larix gmelinii* var. plantations (Du et al. 2009), but substantially lower than *Larix kaempferi*

plantations growing in south of China (Shen et al. 2005) (Fig. 5). It is notable that our estimate for the initial stage is lower than previously published estimates for much smaller stand densities. Compared to studies in larch natural forests, the 229.00 Mg·ha^{-1} of average biomass in KLP is close to 250.96 Mg·ha^{-1} of 120 year-old natural Korean larch forest, and also falls to the range of other natural larch forests in China (199.876 Mg·ha^{-1} of *Larix gmelinii* Rupr.; 277.89 Mg·ha^{-1} of *Larix principis rupprechtii* and 244.63 Mg·ha^{-1} of *Larix sibirica* (Wu et al. 1995).
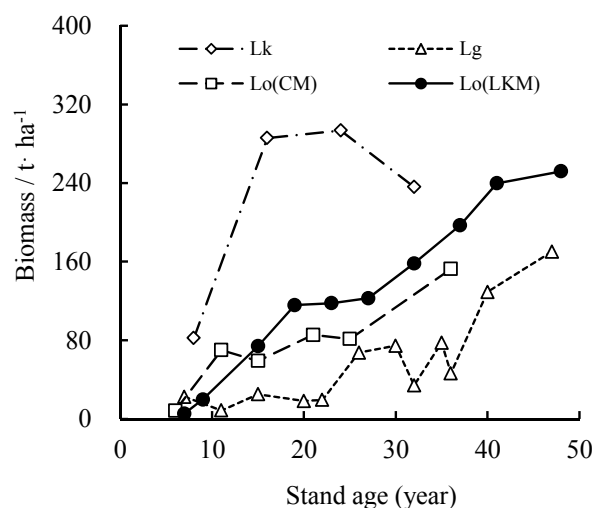

Fig. 5: Comparison of tree biomass with previous estimates of other larch plantations (does not include removed wood). Lk - *Larix kaempferi* plantation (Shen et al. 2005); Lo(CM) - *Larix olgensis* plantation (Wang et al. 2010a); Lo(CM) - *Larix olgensis* plantation we estimated; Lg - *Larix gmelinii* var. plantation (Du et al. 2009).

Even though biomass CS of living trees and understory accounted for 77.23% and 19.35% of the content in these natural forests, DWM levels were found to be 4.47 times higher than in the comparative natural larch forests mentioned. In explanation, we observed that more logging residues from thinning were left on the site, which was unusual occurrence in natural forests.

Our estimates can also be compared with recent estimates from the literatures for CS in context of forest ecosystem (see Table 5). In comparison to the CS of a 36-year-old KLP stand in the Changbai Mountains (Wang et al. 2010a), our estimates in a 37-year-old stand are obviously higher except C in soil. It can be presumed that extensive management slowed tree development, provided low understory vegetation populations, and a lack of logging residues in KLP. Substantial differences in vegetation and SCS emerged when our estimates are compared with the CS estimates for a 35-year-old maple-beech-birch stand after a clear cut harvest in northeast U.S., based on USDA Forest Service FIA data (Smith et al. 2006). On average, the vegetation CS is above that of national-wide larch forests estimated by Zhou et al (2000), and very nearly the same in DWM CS, while soil in this study demonstrated a relatively low CS.

Table 5: Comparison of our estimates with previously published estimates of C stocks for each C pool.

	C stocks (Mg·ha⁻¹)			
	Vegetation	Dead woody materials	Soil	Total
Wang et al. (2010a)	74.1	11.3	101.8	187.2
Smith et al. (2006)	74.5	33.2	69.6	177.3
Our estimate (a)	109.8	29.5	101.6	240.9
Zhou et al (2000)	60.2	20.1	166.5	246.8
Our estimate (b)	73.9	18.1	91.9	183.9
	C stocks (%)			
	Vegetation	Dead woody materials	Soil	Total
Woodbury et al. (2007)	41	11	48	100
FAO (2010)	44	11	45	100
Our estimate (c)	40	10	50	100

Note: Our estimate (a) refers to the 37-year-stand, and our estimate (b) refers to the average of all stand ages, and our estimate (c) refers to the ratio of all stand ages.

The major difference between our estimates of SCS and previous ones is that SCS, as we estimated, is close to KLP in Changbai Mountains but comparatively low for the average levels of national-wide *Larix* forests. Actually, this has been borne out in research on C stocks with a land-use gradient as forest, reforestation, and agricultural land, which indicate that a relatively large proportion of the C loss in soil is due to forest conversion to agricultural land (Pibumrung et al. 2008).

In addition to the numerical estimates discussed above, proportional distribution of CS reported by Woodbury et al. (2007) for U.S. forests and FAO for the whole terrestrial vegetation (FAO 2010) is shown in Table 5. Our estimates are fairly similar, but under those of earlier study, which reported that soil contained 62.9% and vegetation 37.1% of mid-latitude forest C pool (Dixon et al. 1994), and the reference proportion of SCS in mid-latitude temperate forests of China was 63% (Chen 2003). What this suggests is that the afforestation soil of KLP has huge potential for C sequestration and may become an even greater C sink over the long term.

For the annual net C increment, different researchers show various levels by forests; e.g., between 1.483 and 6.402 Mg·ha⁻¹·a⁻¹ of C for afforestation (U.S. EPA 2005). KLP served as a net C sink of about 3.076 Mg·ha⁻¹·a⁻¹ once established, which is a little greater than 2.65 Mg·ha⁻¹·a⁻¹ of *Larix gmelinii* Rupr. plantation (Jiang and Zhou 2002). It must be noted that ANCI of KLP peaked in a 41-year-old stand and amounted to a net C increase in forest ecosystem of 4.9 Mg·ha⁻¹·a⁻¹, which is a comparable to 4.8 Mg·ha⁻¹·a⁻¹ of that in deciduous broad-leaved forest in the warm temperate zone of China (Sang et al. 2002).

Implication of stand management

Associated with shifts in land use, large natural disturbances, such as extensive insect outbreaks or large fires were not found in our study region, but all stands experienced management activities, as described above. Also, density-dependent mortality had not occurred at the stand level; most trees in the plot appeared vigorous, probably a response to forest practices. It is undeniable that artificial regeneration includes greater dominance of commercially desirable tree species, greater control over the number of trees established, and more rapid establishment of trees, all of which increase growth of the desired trees. Jandl et al. (2007) confirmed that land-use changes—such as those resulting from afforestation and management of fast-growing tree species—have an immediate effect on the regional rate of C stock by incorporating CO_2 in plant biomass.

Young KLP stands increased total C storage in dense stands, except where severe competition significantly reduced growth rates (David et al. 1997). Tending, pruning, and the predominant forest management practices, like pre-commercial thinning and commercial thinning, were conducted to focus growth on fewer trees, and to reduce competition among plants. These interventions concentrated stand growth on fewer larger trees, with little overall change in C storage.

The greatest CS accumulation was found in a small number of live trees from 41 ages on, which dominated in term of FECS. This confirmed that FECS had increased not only in quantity but also in quality, as fewer large trees in the 48-year-old stand concentrated more C than a greater number of smaller trees. Some have calculated that harvesting timber from an over-mature forest can sequester substantial additional C because the forest is currently sequestering little additional C and the timber can continue to store C for decades in long-term solid wood products (Gorte 2009). As a management cycle, after the harvest rotation, the newly established stand can sequester large amounts of C through its vigorous growth.

After cutting some of the existing vegetation on a site, slash treatments (like rolling, chopping and crushing) are not designed to compact the biomass and accelerate DWM deterioration. DWM accumulation was a little greater in KLP with mean value 18.051 Mg·ha⁻¹, and lower in natural Korean larch forests and Korean pine forests, with mean values of 15.12 and 17.64 Mg·ha⁻¹ respectively (Wang et al. 2010a). Depending largely on the local climate, it would typically take several months to years for the fallen materials begins to deteriorate, and to release C to atmosphere and incorporates C as organic matter in the soil. DWM turnover is also affected by the C: N (nitrogen) ratio and other determinants of DWM quality (Guo and Gifford 2002).

With regard to forest soil cycles, soil C is lost following thinning and timber harvesting, reducing canopy cover, and disturbing the surface and thus accelerating decomposition rates (Robert et al. 1991; David et al. 1997). Additionally, a portion of the C sequestrated by soil is then quickly absorbed by new growth resulting from the treatment (Gorte 2009). By leaving the thinning residues on the soil surface, however, their input into the soil may compensate for losses (Heleen and Sheila 1999). The initial C accumulation occurs in the forest floor. The dynamic pattern of long-term equilibrium of SCS depends on climate, which influences plant growth and the turnover rate of organic matter. Litter-derived C was moved into the mineral soil, but it remained unstabilized and was lost rapidly through decomposi-

tion (Susan 2000; Hagedorn et al. 2003).

After several decades, more C is moved to the mineral soil (Hooker and Compton 2003; Johnson et al. 2003; DeGryze et al. 2004). Other studies have shown that some old-growth forests, even during the later stages of succession, continue to accumulate C in their soils overtime (Silver et al. 2004; Zhou et al. 2006). Rationally, forest land has the potential to increase soil C sequestration if proper practices and management are implemented, such as reduced thinning or harvest residue removal (Richardson et al. 2002).

Conclusion

Our research supports a growing consensus that afforestation of cropland increases CS, and shows certain predictable effects after implementing GGP in China. The estimated forest ecosystem carbon stock of Korean larch plantations across chronosequence is useful for CS estimate on (two-way) transitions between agriculture and forest, and dynamics following afforestation. In this study, the amount of total C storage in the agricultural land was estimated at 88.2 Mg·ha^{-1}. We estimated the distribution of CS to stand-level, individual-sector, and forest ecosystem of KLP ranging in age from 7 to 48 years, for afforestation conversions between forestland and agricultural land based on plot-level investigation data and samples.

Though Korean larch has a lower c than some broadleaved species, the fast development of KLP brings along high growth of CS, making the appropriate species selection for afforestation crucial in the Lesser Khingan Mountains area. Overall KLP forest ecosystem C was estimated at 183.9 Mg·ha^{-1}, combined within vegetation (73.9 Mg·ha^{-1}), DWM (18.1 Mg·ha^{-1}) and soil (91.9 Mg·ha^{-1}). Worth noting, the 48-year-old forest sequestered 290.3 Mg·ha^{-1} net C, or 4.3 Mg·ha^{-1}·a^{-1}, showing superior capacity in C sequestration.

The growth of vegetation biomass does create a massive influx of C, which does increase the C accumulation in DWM and soil. Therefore, differences in CS between communities were primarily the result of differences in vegetation biomass, soil constitutes the largest pool, and the increasing BD and decreasing of SCS will both make more soil C gains. Furthermore, these appropriately managed native ecosystems will have great potential for sequestration in the future.

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