

Title	Applicability of synthetic aperture radar (SAR) to evaluate leaf area index (LAI) and its growth rate of rice in farmers ' fields in Lao PDR
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1 Applicability of Synthetic Aperture Radar (SAR) to Evaluate Leaf Area Index (LAI) and
2 its Growth Rate of Rice in Farmers' Fields in Lao PDR

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11 Highlights

- 12 • This study applied SAR to estimate LAI and its growth rate in Lao PDR.
- 13 • Back scattering coefficient (BSC) of SAR was correlated with LAI and NDVI.
- 14 • Increase of BSC against day represented LAI growth.

15
16 ABSTRACT

17 Rice is the most important crop in Lao People's Democratic Republic (Lao PDR).
18 Synthetic aperture radar (SAR) is proposed as a more suitable method to evaluate rice
19 growth in this area because it is independent from cloud and solar illumination. This
20 study analyzed the relationship between the back scattering coefficient (BSC) in SAR
21 images and leaf area index (LAI) of rice. Here, we discuss the applicability of SAR to
22 estimate LAI and its growth rate in farmers' fields in Lao PDR. 30 farmers' paddy fields
23 were selected for surveying throughout the growth period in the wet season of 2013, and
24 both LAI and normalized difference vegetation index (NDVI) were measured at 4 time
25 periods before the heading period for each field. X-band SAR images from the
26 COSMO-SkyMed system (SAR) were used in this study. BSC was significantly
27 correlated with LAI and NDVI. BSC at 28 of 30 fields was positively correlated with
28 days after transplanting (DAT), and 10 of these results were significant. The increased
29 rate in BSC obtained at the fields where BSC and DAT had a significant correlation,
30 were significantly correlated with that in LAI. This finding suggests that if SAR images
31 demonstrate significant increases of BSC against DAT, the increased rate may also
32 represent LAI growth rate, although uncontrollable water levels and weeds occasionally
33 interrupt observation. This study demonstrates the capacity of SAR to evaluate rice
34 production in developing countries.

35
36 Keywords:

37 Back scattering coefficient (BSC); farmers' fields; LAI; NDVI; rice; Synthetic aperture
38 radar (SAR).

39

40 **1. Introduction**

41 Rice is undoubtedly the most important crop in the Lao People's Democratic Republic
42 (Lao PDR), and approximately 70% of the total calories in the Lao diet come from rice
43 (Maclean et al., 2002). While improving its productivity is strongly recommended, the
44 information about rice growth characteristics in farmers' fields is limited (Bell and Seng,
45 2003; Fukai et al., 1999; Inamura et al., 2003). Hirooka et al. (2015) measured leaf area
46 index (LAI) and its growth rate using a plant canopy analyzer and reported that rice
47 production was closely associated with LAI growth rate. However, because application
48 of a plant canopy analyzer is not suitable on a regional scale, the evaluation by satellite
49 based remote sensing is recommended.

50 Most rice production in Lao PDR is conducted in the rainy season (Schiller, 2006),
51 during which cloudy conditions often interrupt satellite observation in visible and near-
52 infrared range. Accordingly, remote sensing based on synthetic aperture radar (SAR) is
53 proposed as a more suitable method to evaluate rice growth in this area because the
54 observation is independent from cloud and solar illumination (Chakraborty et al., 1997).
55 The radar transmits a pulse and then measures the time delay and strength of the
56 reflected echo, where the ratio of scattered and incident microwave energy is termed the
57 back scattering coefficient (BSC) (Moran et al., 2002). SAR uses polarized radiation
58 and, therefore, can exploit polarization signatures of the imaged scatters for obtaining
59 more information about the scatter's structure (Bamler, 2000). Although previous
60 studies investigated the applicability of SAR to estimate LAI (Inoue et al., 2014; Maki
61 et al., 2015), the estimation accuracy has not attained practical level. The present study
62 analyzed the relationship between SAR images and LAI of rice measured by Hirooka et
63 al. (2015) and discusses the applicability of SAR to estimate LAI and its growth rate in
64 farmers' fields in Lao PDR. The results showed although the accuracy was still the
65 problems to estimate LAI, analyzing a sequence of BSC may provide a strategy to
66 applicate SAR to evaluate rice production in developing countries.

67

68 **2. Materials and Methods**

69 2.1. Overview and test sites

70 This study used LAI data from farmers' fields in Vientiane province in 2013, Lao PDR
71 (18°01' - 18°30'N, 102°24' - 103°02'E, 168 - 178 m asl.), observed by Hirooka et al.
72 (2015). We analyzed SAR data in relation to LAI, together with the normalized

73 difference vegetation index (NDVI) measured in the same fields.

74 30 farmers' paddy fields in this area were selected for surveying throughout the growth
75 period (Hirooka et al., 2015). We selected the fields that had open space in the direction
76 of satellite orbit (west and approximately 45° in the incident angle) and that were
77 surrounded by relatively flat paddy fields (at least 1 ha in the area). The mean air
78 temperature for the measuring period (from 22 July to 16 September) was 28.0 °C. The
79 longitude and latitude of the selected fields were recorded by Global Positioning System
80 (GPSMAP 62SJ, Garmin International, Inc., Kansas City). The cultivation methods
81 (direct seeding/transplanting, fertilizer, planting density and cultivar) of rice plants and
82 field conditions (standing water and weeds) in the farmers' fields under investigation
83 were checked by the authors' observation and interviews to farmers. The fields where
84 the maximum depth of standing water exceeded more than 30 cm were classified as
85 deep water fields, and the fields where weeds covered a maximum of 20% or more were
86 classified as weedy fields in this study.

87 2.2. LAI measurement and analysis (Hirooka et al., 2015)

88 LAI was measured using a plant canopy analyzer (LAI-2200, LI-COR, Inc., Nebraska)
89 with a single sensor mode in a sequence of two above and four below canopy with 5
90 replications at each field. To reduce the influence of the adjacent fields and the operator,
91 a 90° view-cap was applied to the optical sensor. Measurements were conducted 4 times
92 before the heading period (22 - 24 July, 10 - 12 August, 30 August - 1 September and 16
93 - 18 September). Since LAI linearly increased during the measurement, LAI growth rate
94 was calculated using the following linear function (Eq (1); Hirooka et al., 2015).

$$95 \text{ LAI} = a * \text{DAT} + b \quad (1)$$

96 DAT denotes days after transplanting, a represents LAI growth rate, and b represents
97 approximate LAI at the transplanting date.

98 2.3. NDVI measurement

99 For measuring spectral reflectance of rice canopies, we used a spectroradiometer
100 (MS-720, EKO Instruments Co., Ltd., Tokyo). MS-720 measures radiation from 350 nm
101 to 1050 nm by 3.3 nm intervals. We measured the sky radiation with a FOV 180°
102 attachment and the plant reflection with a FOV 45° attachment from 1 m above the rice
103 canopies, with 3 replications at each field when we measured LAI. We calculated
104 canopy reflectance by dividing plant radiation by sky radiation. We calculated the
105 normalized difference vegetation index (NDVI) using canopy reflectance in RED
106 (620-670 nm) and NIR (841–875 nm) (Eq (2)).

$$107 \text{ NDVI} = (\text{reflectance in NIR} - \text{reflectance in RED}) / (\text{reflectance in NIR} + \text{reflectance in RED}) \quad (2)$$

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109 2.4. SAR images

110 X-band SAR images from the Constellation of Small Satellites for the Mediterranean
111 Basin Observation COSMO-SkyMed system (ScanSAR Wide Region mode, HH
112 polarization) were used in this study to acquire high temporal and spatial-resolution
113 SAR data. COSMO-SkyMed can supply high temporal and spatial-resolution data by
114 operating 4 satellites on the same orbit. All COSMO-SkyMed images used in this study
115 were acquired during ascending orbit. The incidence angle for data acquisition was
116 approximately 45°. Spatial resolution was adjusted to 30 m by multi-look processing
117 and spatial filtering to reduce speckle noise. The 3 × 3 pixel Lee filter (Lee, 1980) was
118 applied to the images used in this study. Back scattering coefficients (BSC) of SAR
119 images is increased as rice plants grow in the paddy fields (Fig.1). Eight SAR images
120 were obtained from the period between transplanting and heading: on 22 and 30 July, 7,
121 15, 23 and 31 August and 8 and 16 September. 4 SAR images on 22 July, 7 August, 31
122 August and 16 September were selected to analyze the relation with LAI and NDVI
123 measured on 22 - 24 July, 10 - 12 Aug, 30 Aug - 1 Sep and 16 - 18 Sep, respectively.

124 **3. Results and discussion**

125 Back scattering coefficient (BSC) at the investigated fields in SAR images ranged
126 from -18.3 to -1.57. LAI and NDVI ranged from 0.03 to 3.60 and from -0.24 to 0.81,
127 respectively. BSC at 28 of 30 fields had a positive correlation with days after
128 transplanting (DAT), corresponding with rice growth (Fig. 1). However, only 10 of
129 these results were significant. Observations at the investigated fields indicated that
130 non-significance was partly caused by deep water or weeds (see Fig. 3).

131 Fig. 2a shows that BSC was significantly correlated with LAI (LAI; $r = 0.584$, $p <$
132 0.001). Although the value was slightly lower than that previously reported (0.75 by
133 Inoue et al., 2014), the difference might be derived from that between X-band and
134 C-band. Previous studies also reported that BSC at rice fields showed saturation greater
135 than 3 in LAI similar to the levels NDVI often suggested (see Fig2c; Capodici et al.,
136 2013; Inoue et al., 2014). However, BSC in this study did not show such saturation due
137 to moderate correlation with LAI. Deep water and weeds are generally the factors that
138 disturbed the relationship between LAI and BSC because BSC is decreased by water
139 (Martinez and Toan, 2007) and increased by weeds (Liew et al., 1998). In this study,
140 however, the relationship did not improve even if weedy and DW fields were excluded
141 from the analysis (Table 1). Fig. 2a and Table 1 shows that BSC and LAI had a closer
142 correlation at the fields where BSC and DAT had a significant correlation. These results
143 suggest that the possibility of estimating LAI is dependent on location and that the
144 observed increase in BSC with DAT is a required condition. Field heterogeneity

145 (Miyaoaka et al., 2013) or orientation of ridge in paddy fields (Yamaguchi et al., 2005)
146 may cause such locational error. Although further study is necessary, selection of
147 observation point on the basis of the relation between BSC and DAT in previous seasons
148 probably improves the estimation accuracy for LAI with BSC.

149 Fig. 2b demonstrates that BSC was also correlated with NDVI ($r = 0.574$, $p < 0.001$).
150 Although LAI and NDVI displayed a nonlinear relationship (Fig. 2c), no distinct
151 difference was observed in the relationship between BSC and LAI and that between
152 BSC and NDVI (Fig. 2a and Fig. 2b). Further studies are necessary to determine what
153 structural factors in rice canopy affect BSC.

154 The increased rates of BSC against DAT obtained in the fields where BSC and DAT
155 had a significant correlation were also significantly correlated with LAI growth rate (the
156 regression line in Fig. 3). However, those fields in which BSC and DAT showed a
157 non-significant correlation tended to yield lower values of BSC increase rate that
158 expected from the regression line. This finding suggests that if a significant increase of
159 BSC against DAT was obtained, the increased rate may represent LAI growth rate.
160 Hirooka et al. (2015) reported that LAI growth rate was closely associated with soil C
161 and N levels, which is a major indicator of soil fertility and consequent rice production
162 in the study area. These facts suggest that soil fertility and rice productivity could be
163 estimated from BSC even though LAI cannot be directly estimated from BSC.

164 Although LAI ordinarily shows curvilinear growth such as sigmoid, this study
165 estimated the growth rate by a linear function (Eq. 1) according to Hirooka et al. (2015).
166 The linear growth indicates that the observation was conducted after exponential growth
167 and before saturated growth. Low LAI (see Fig. 3a) may help rice to keep linear growth
168 of LAI before heading. To follow rice growth more precisely, more frequent
169 measurements are necessary especially just after transplanting and around heading.
170 Such frequent observation of LAI and BSC might improve the estimation of rice
171 growth.

172 Rice production in Lao PDR is currently conducted on small and untidy paddy fields
173 where many trees are left uncut (Kosaka et al., 2006; Miyagawa et al., 2013).
174 Uncontrollable water levels (drought and deep water) and weeds often constrain rice
175 production in this area (Inamura et al., 2003; Inthavong et al., 2011). These factors are
176 unfavorable for evaluating rice growth by SAR images. The dependence on incidence
177 angle and azimuth angle of the SAR sensor in the relationship between BSC and LAI
178 should also be analyzed further in order to accurately estimate LAI (Gautier et al., 1998).
179 Despite the remaining limitations, this study has demonstrated the capacity of SAR to
180 evaluate rice production in developing countries. Combining an area map of planted rice

181 as well as planting dates both of which are obtained from SAR images (Miyaoka et al.,
182 2013; Maki et al., 2015) may help a more accurate evaluation of rice productivity.

183

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257 Figure captions

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259 Fig.1 The map of Google earth (left) and synthetic aperture radar (SAR) images (center
260 and right) for a part of the research area. Back scattering coefficient (BSC) is
261 gray-scaled in the SAR images. The increase of BSC (gray in 22 July to white in 16
262 September) corresponded to the rice growth in paddy fields.

263

264 Fig. 2 Changes in the back scattering coefficient (BSC) with days after transplanting
265 (DAT) at the two fields where BSC and DAT had a significant correlation. The slope of
266 the regression line was defined as rate of BSC increase.

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268 Fig. 3 Relationship between (a) back scattering coefficient (BSC) and leaf area index
269 (LAI), (b) BSC and normalized difference vegetation index (NDVI), (c) LAI and NDVI.
270 S: the field where BSC and DAT had a significant correlation. N: the field where BSC
271 and DAT had a non-significant correlation. DW: the field that had more than 30 cm
272 depth of standing water. Weed: the field covered by more than 20% weeds at the
273 maximum.

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275 Fig. 4 Relationship between leaf area index (LAI) growth rate ($\text{m}^2 \text{m}^{-2} \text{day}^{-1}$) and back
276 scattering coefficient (BSC) increase rate (day^{-1}). The line was regressed by the field
277 where BSC and DAT had a significant correlation (S). The symbols are the same in Fig.
278 3; The fields which were classified into DW or Weed at least one time in Fig. 3 were
279 defined as DW or Weed fields, respectively.

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281 Table 1 Correlation coefficients of back scattering coefficient (BSC) with leaf area
282 index (LAI and normalized difference vegetation index (NDVI). Except DW: DW fields
283 were excluded from the correlation; Except Weed: Weed fields were excluded from the
284 correlation; Except N: the fields where BSC and DAT had a non-significant correlation
285 were excluded from the correlation; see Fig. 3.

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1 Table 1 Correlation coefficients of back scattering coefficient (BSC) with leaf area
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4 from the correlation; Except N: the fields where BSC and DAT had a non-significant
5 correlation were excluded from the correlation; see Fig. 3.

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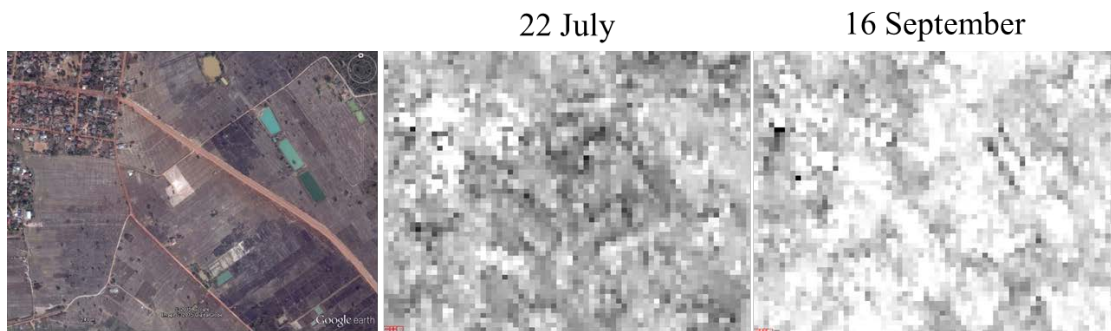
	LAI	NDVI
All	0.584	0.574
Except DW	0.551	0.509
Except Weeds	0.603	0.585
Except N	0.766	0.593

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15 (center and right) for a part of the research area. Back scattering coefficient (BSC) is
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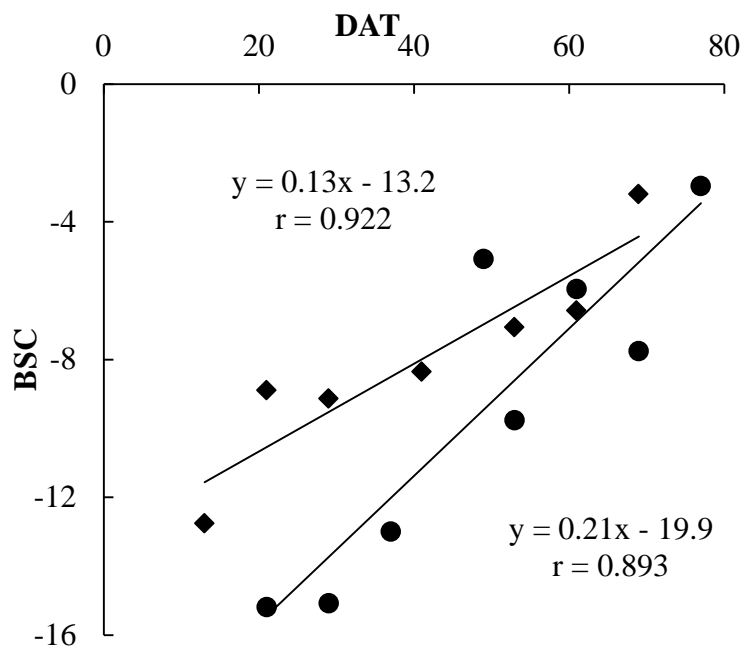
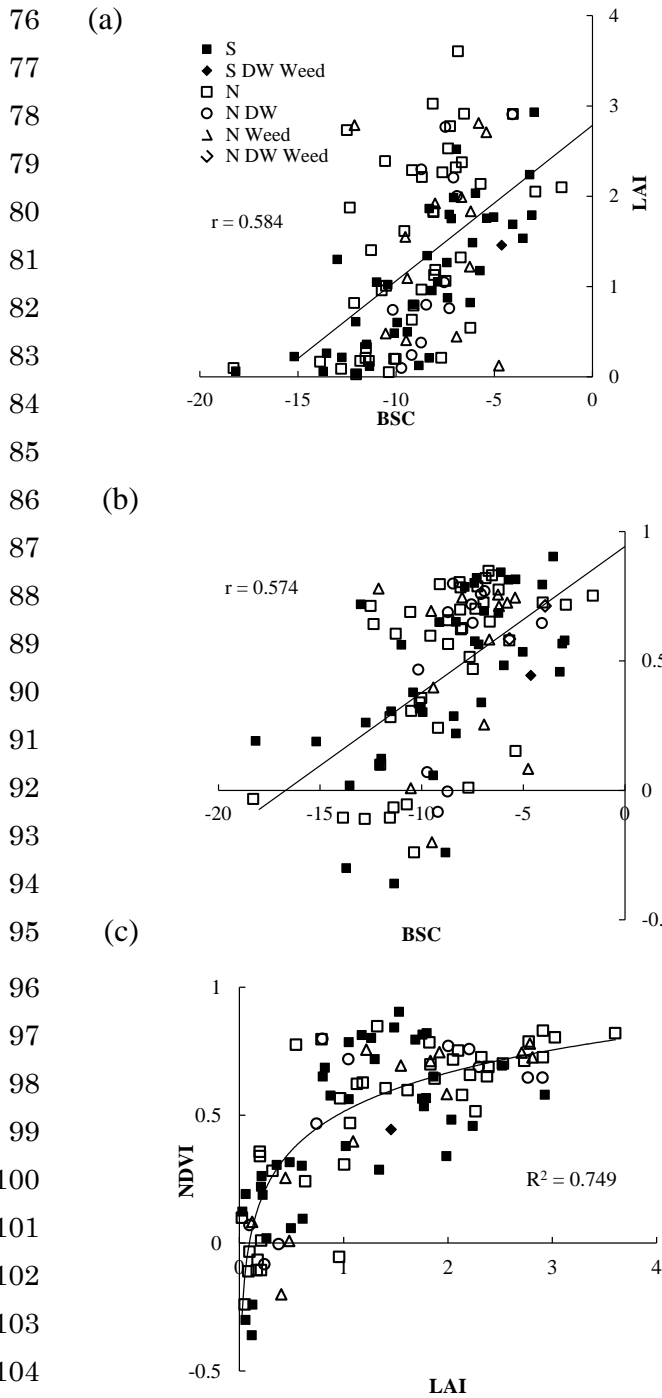


Fig. 2 Changes in the back scattering coefficient (BSC) with days after transplanting (DAT) at the two fields where BSC and DAT had a significant correlation. The slope of the regression line was defined as rate of BSC increase.



106 Fig. 3 Relationship between (a) back scattering coefficient (BSC) and leaf area index
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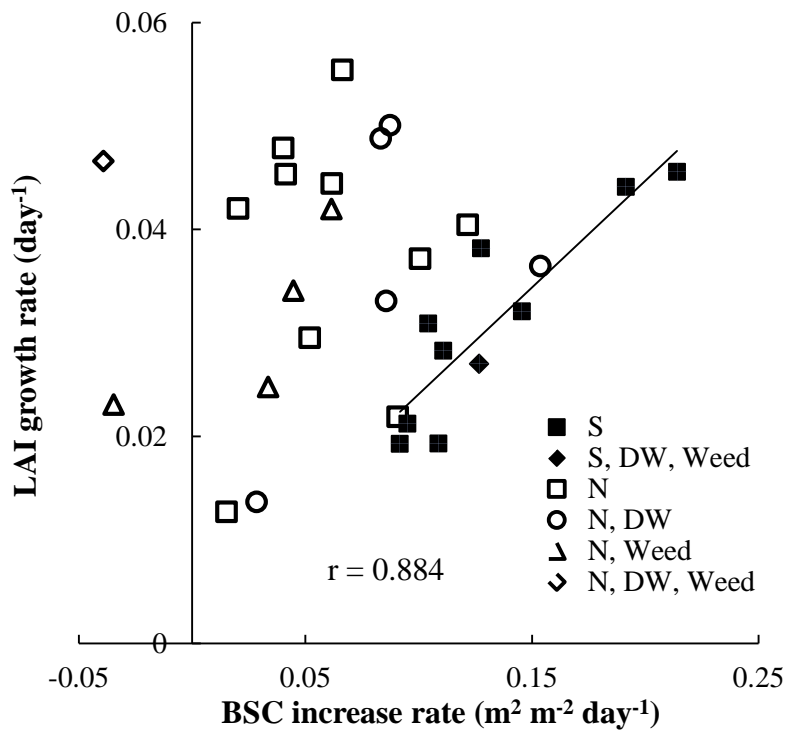


Fig. 4 Relationship between leaf area index (LAI) growth rate ($\text{m}^2 \text{m}^{-2} \text{day}^{-1}$) and back scattering coefficient (BSC) increase rate (day^{-1}). The line was regressed by the field where BSC and DAT had a significant correlation (S). The symbols are the same in Fig. 3; The fields which were classified into DW or Weed at least one time in Fig. 3 were defined as DW or Weed fields, respectively.