ASSESSING THE LEANING, BENDING, AND SINUOSITY OF SAPLING-SIZE TREES

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ABSTRACT

Many factors result in trees with non-straight stems. An important prerequisite to investigating the causes of stem deformity is an ability to assess stem displacement. An ideal system would be easy to implement, be objective, and result in an index that incorporates the essential characteristics of the stem deformity into a dimensionless number. We tested a number of indices that could be measured and calculated from a photo taken from the side showing the tree's greatest deformity. Image analysis software was used to measure the characteristics that define the stem displacement and calculate an index of deformity. This system was tested on trees completing their fifth growing season in a long-term study of the effects of container cavity size and copper root pruning on longleaf pine (*Pinus palustris* Mill.) planted on moderately well-drained, gently sloping soils in central Louisiana.

INTRODUCTION

A field experiment of the effects of container cavity size and root pruning with copper on longleaf pine was established in November, 2004 in central Louisiana (N31°09.7342' ,W092°40.0396'). Sapling stems were first observed to be leaning after hurricane Gustav (September, 2008) and again in August, 2009. Some of the trees recovered from leaning, some did not, and some became sinuous during their recovery. A method was needed to quantify the degree of leaning so that it could be correlated with other tree characteristics.

There is no shortage of ways to quantify stem displacement, such as leaning, bending, and sinuosity, but there does not appear to be a standard way. In a study of crooked stem form with loblolly pine (*P. taeda* L.), Goddard and Strickland (1964) examined but dismissed the ocular estimates of Barber (1961), the binary classification of Mergen (1955), and the three crook categories of Littlefield and Eliason (1956). They modified the method of Perry (1960) for their estimates of stem crookedness (Goddard and Strickland 1964). Hans (1972) developed an instrument for assessing stem straightness and reported his results in three numbers: maximum deviation, angle, and number of bends. Cooper and Ferguson (1981) used subjective visual scores. Shelbourne and Namkoong (1966) used a photogrammetric technique to measure many variables associated with stem straightness. Adams and Howe (1985) dismissed photographic techniques as being too expensive and developed a simple index based on displacement. Cremer (1998) provided an in-depth analysis of stem recovery from bending using just the angle at the base of the stem and along the main displaced segment of the stem.

MATERIALS AND METHODS

After Hurricane Gustav in September, 2009, we began to photograph saplings from a long-term study of the effects of container cavity size and copper-caused root pruning on longleaf pine grown in containers before outplanting in November, 2004 on moderately well-drained, gently sloping soils in central Louisiana (Sword Sayer and others 2009). Digital photographs of each tree were taken from an angle perpendicular to the plane of greatest stem displacement. Twelve trees with various degrees of displacement were selected for this study. One of the selected trees was documented through time. A vertically held scale pole was included in each photograph. We used the photos as taken, but did examine the possibility of rectifying them to remove parallax effects. Measurements listed below were done using Sigma-Scan® from Jandel. Some of the measurements and calculations were directly from the literature, while others were new ideas. We also asked 10 people to rank 12 trees for stem displacement, on a scale of 1 to 5, based on the photographs taken. A straight tree is a 1 and a toppled tree very close to ground is a 5.

The measurements done on photographs of these trees are illustrated in figure 1: (a) the length of the shortest line from the base to the tip of the stem (fig 1A); (b) the area enclosed by the shape of the stem and the shortest line from the base to the tip of the stem (fig 1A); (c) the smallest rectangular area that fully encloses the main stem which may or may not include branches (fig 1B); (d) the height of the stem (fig 1C); (e) the area of the deflection between the shape of the stem and a vertical line centered at the base of the stem and extending to the tip of the stem (fig 1C); (f) the maximum deflection horizontal distance between a vertical line centered at the base of the stem and the point on the stem furthest from this vertical line (fig 1D); (g) the height of the maximum deflection point (fig 1D); (h) the height of the first deflection point on the stem (fig 1E); (i) the length of the stem following the shape of the stem (fig 1F); and (j) the angle between the stem base and the maximum

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deflection point on the stem (fig 1F); (k) the number of separate shortest line areas obtained by measurement (b) (fig 1A); (l) the number of separate deflection areas obtained in measurement (e) (fig 1C). The labels for k and l do not appear on the figure. In figure 1A, the left tree has one and the right tree has two shortest line areas. Both trees in figure 1C have two deflection areas. The height of first deflection point for the left tree in figure 1E is zero. Note that the rectangular area (measurement c) encloses the whole stem while the shortest line area (measurement b) and the deflection area (measurement e) extend only to the center of the stem.

Using the measurements a through l, twelve possible stem displacement indices were calculated and evaluated. Measurements g and h were ultimately not used in any of the indices presented here.

No. 1- Sinuosity index as defined by Wikipedia (2011) is the actual path length (the stem length, measurement i) divided by the shortest path length (measurement a).

No. 2- Since with the No. 1 index a leaning but otherwise straight tree would have a value of one, the same as that of the non-displaced tree, this index is the stem length (measurement i) divided by stem height (measurement d).

No. 3- Goddard and Strickland (1964) defined “Crook Index” as the number of crooks (measurement l) multiplied by the deviation of the largest crook (the maximum deflection distance, measurement f).

No. 4- Temel and Adams (2000) used a sinuosity index that is the number of crooks multiplied by the deviation of the largest crook (measurement f) and then divided this number by the stem radius. They only calculated their index for the second interwhorl from the top of the tree and used the radius of this segment. Since we calculated an index for the whole tree, we used the stem radius at 4.5 feet as our divisor.

No. 5- Temel and Adams (2000) worked only within the interwhorl; so, they did not account for taller versus shorter trees. We employed a modification where the index was further divided by tree height (measurement d).

No. 6- Cremer (1998) evaluated the tilt and posture of trees that are simply angles of lean on various parts of the stem. We evaluated the angle to the largest deviation from vertical on the stem (measurement j).

No. 7- The remaining indices are simply ideas that seemed reasonable to try. The first is the sum of all of the deflection areas (measurement e) divided by height (measurement d).

No. 8- A variation of the No. 7 index is to divide the area of the smallest rectangle possible (measurement c) by stem height (measurement d) and by diameter at breast height.

No. 9- The index is derived from multiplying the shortest line area (measurement b) by the number of bends (measurement k).

No. 10- A different variation of the No. 9 index is to divide the shortest line area (measurement b) by stem height (measurement d).

No. 11- Angle seems to be one of the characteristics that the eye of the observer is drawn to; yet, it does not account for multiple bends. Therefore, two additional modifications of the No. 6 index were attempted. The first is to multiply the angle of maximum deflection (measurement j) by the number of separate areas created by the shortest line(measurement k).

No. 12- The second is to multiply the angle of maximum deflection (measurement j) by the number of separate deflection areas created by a vertical line (measurement l).

RESULTS AND DISCUSSION

The advent of digital photography and computer image-analysis software have made photographic techniques practical for research studies, even if they may not be as useful in large-scale surveys. They have the advantage of minimizing complex measurements in the field while providing a permanent record of the measured trees. Photography is a useful tool in sinuosity measurements. It allows documentation of all characteristics, even those that were not thought of at the initial measurements. It allows access to points on the tree that would be difficult or unsafe to get to with a ladder or lift. The form of the tree is also less affected by the measurement process.

On the negative side, measurements are only two-dimensional and some parts, like the stem base and bud tip, may be hard to see. Proper scaling can be a problem. While not done in our earliest attempts we have found it important to guarantee that the base of the tree is visible and that the scale pole is in the same plane as the subject tree. It is probably best to record easily obscured measurements like diameter at breast height in the field rather than from the photograph. On average, the photo measurements were still less than 0.01 foot different in diameter and the length measurements were on average less than 0.22 feet different from field measurements. Given these small differences, it was decided that image rectification was an unnecessary step.

Figure 2 shows the 12 trees which were ranked subjectively for stem lean, bend, and sinuosity. Their digital measurements are summarized table 1. The same measurements were also done on a single tree through time in figure 3 but the data are not shown. Using the measurements obtained digitally, twelve possible sinuosity indices for the 12 trees in figure 2 are presented in table 2. Indices for a single tree through time are presented in table 3.

Two overarching criteria were used for the purposes of evaluating indices. The first is how well an index agreed with the subjective ranking that a reasonable person would give to a tree and is evaluated with table 2. The second criterion is how well the index showed the recovery from stem displacement by a tree through time as shown with table 3.

Subjective rankings are faster and by definition agree with what we feel is the correct rating. What they lack is repeatability between different observers and the ability to detect very subtle changes. Most of the objective measures tested have some good features. Ultimately we decided that for our use, No. 8 index, which is reported in tables 2 and 3 and based on the smallest possible rectangular area (measurement c), along with height (measurement d) and dbh, is the best. Henceforth we will refer to this method as the rectangular area index (RAI).

One important characteristic of the RAI is that it is dimensionless. Even though all of our calculations were done in feet because of the scale of the height pole, the index would be the same if we used the metric system or any other units. Only three other indices are dimensionless, No. 1, No. 2, and No. 4 (Tables 2 and 3). Indices No. 1 and No. 2 do not have a great range of values; thus trees of various degree of stem displacement have very similar indices. Furthermore, changes in a tree through time are more difficult to detect as shown in table 3. The No. 4 index has much potential since it appears to work well and is previously published (Temel and Adams 2000). However, in applying it to whole trees, there was disagreement among users as to the appropriate way to count the number of crooks. Obtaining the measurements for the RAI is a very basic process with little room for user variation so it is easy to repeat with different users.

In conclusion, none of the indices tested was perfect and none was useless. We felt that the RAI was the most useful for our purposes and it will get extensive use as we try to correlate the recovery of bent stems to their root system architecture. The RAI could also serve as a useful index in many of the genetic studies that the literature (Adam and Howe, 1985; Barber, 1961;Cooper and Ferguson, 1981; Goddard and Strickland, 1964) indicates are the primary use of such indices.

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Table 1—Measurements,as described in figure 1, used to calculate the indices for the 12 longleaf pine saplings shown in figure 2 beginning their sixth growing season in central Louisiana: (a) shortest line length (SLL); (b) shortest line area(SLA); (c) rectangular area (RA); (d) height (H); (e) deflection area (DA); (f) maximum deflection distance (MDD); (g) maximum deflection height (MDH); (h) first deflection height (FDH); (i) stem length (SL); (j) angle to maximum deflection; (k) number of separate SLA (NS); and (l) number of DA (NV).

ID	DBH	(a) SLL	(b) SLA	(c) RA	(d) H	(e) DA	(f) MDD	(g) MDH	(h) FDH	(i) SL	(j) A	(k) NS	(l) NV
	ft	ft	ft^2	ft^2	ft	ft^2	ft	ft	ft	ft	degrees		
5	0.17	11.52	0.63	5.61	11.49	1.93	0.22	3.92	0.00	11.50	3.20	2	1
1	0.13	9.94	0.69	6.09	9.92	1.37	0.25	7.58	1.07	9.97	1.91	4	3
11	0.13	8.45	0.89	4.58	8.60	2.73	0.44	4.49	0.00	8.65	5.55	1	1
6	0.17	12.55	5.93	25.46	12.49	5.47	1.71	12.49	0.00	12.77	7.78	1	2
12	0.15	13.85	5.99	35.75	13.62	9.38	2.29	13.62	0.73	13.93	9.53	1	1
8	0.10	8.20	2.71	8.30	8.17	4.16	0.81	4.95	0.00	8.32	9.30	1	1
7	0.14	9.90	5.01	16.73	9.83	3.11	1.16	9.83	0.97	10.22	6.70	2	2
9	0.07	5.98	2.31	6.67	5.94	2.06	0.85	3.88	0.00	6.40	12.35	1	2
10	0.13	9.35	6.99	15.57	9.32	8.18	1.44	6.19	0.00	9.91	13.11	1	1
2	0.12	6.69	2.89	7.63	6.58	1.72	0.64	4.59	0.92	7.03	7.96	2	3
3	0.11	8.70	9.56	36.82	4.79	7.58	7.16	4.79	0.00	9.54	56.26	2	1
4	0.07	5.26	7.06	15.43	3.57	1.21	4.09	3.25	1.20	7.02	51.56	1	2

Table 2—Evaluated indices calculated for the 12 subjectively ranked longleaf pine saplings shown in figure 2 beginning their sixth growing season in central Louisiana. Subjective ranking (SR) was on a scale of 1 to 5 with 1 being a straight stem. For conciseness the following abbreviations are used: A=angle to maximum deflection; DA=deflection area; H=height; MDD=maximum deflection distance; NS= number of areas defined by the shortest line from base to tip; NV= number of areas defined by a vertical line centered at the stem base; R=stem radius at 4.5 feet; RA=rectangular area; SL=stem length; SLA=shortest line area; SLL=shortest line length. No. 1= SL/SLL; No. 2=SL/H; No. 3= Goddard and Strickland=NV*MDD; No. 4= Temel and Adams=(NV*MDD)/R; No. 5= modified Temel and Adams= NV*MDD)/(R*H); No. 6= A; No. 7= DA/H; No. 8 = RA/(H*R*2); No.9=SLA/NS; No. 10= SLA/H; No. 11=A/NS; No. 12=A/NV.

ID	SR	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12
				ft		ft^{-1}	degrees	ft		ft^2	ft	degrees	degrees
5	1.2	1.00	1.00	0.22	2.53	0.22	3.20	0.17	2.82	1.26	0.05	6.40	3.20
1	2.0	1.00	1.01	0.76	11.57	1.17	1.91	0.14	4.68	2.75	0.07	7.64	5.73
11	2.3	1.02	1.01	0.44	6.94	0.81	5.55	0.32	4.23	0.89	0.10	5.55	5.55
6	2.5	1.02	1.02	3.42	41.03	3.28	7.78	0.44	12.24	5.93	0.47	7.78	15.57
12	2.6	1.01	1.02	2.29	30.64	2.25	9.53	0.69	17.57	5.99	0.44	9.53	9.53
8	3.3	1.01	1.02	0.81	15.92	1.95	9.30	0.51	9.98	2.71	0.33	9.30	9.30
7	3.5	1.03	1.04	2.31	32.43	3.30	6.70	0.32	11.95	10.02	0.51	13.41	13.41
9	3.8	1.07	1.08	1.70	45.53	7.66	12.35	0.35	15.06	2.31	0.39	12.35	24.69
10	3.8	1.06	1.06	1.44	21.42	2.30	13.11	0.88	12.41	6.99	0.75	13.11	13.11
2	3.8	1.05	1.07	1.93	32.20	4.90	7.96	0.26	9.71	5.78	0.44	15.93	23.89
3	4.8	1.10	1.99	7.16	132.72	27.73	56.26	1.58	71.26	19.12	2.00	112.51	56.26
4	4.8	1.33	1.96	8.18	225.34	63.03	51.56	0.34	59.47	7.06	1.97	51.56	103.11

Table 3—Stem displacement indices through time for a longleaf pine sapling tree shown in figure 3 planted in November, 2004 in central Louisiana. For conciseness the following abbreviations are used: A=angle to maximum deflection; DA=deflection area; H=height; MDD=maximum deflection distance; NS= number of areas defined by the shortest line from base to tip; NV= number of areas defined by a vertical line centered at the stem base; R=stem radius at 4.5 feet; RA=rectangular area; SL=stem length; SLA=shortest line area; SLL=shortest line length. No. 1= SL/SLL; No. 2=SL/H; No. 3= Goddard and Strickland=ND*MDD; No. 4= Temel and Adams=(NV*MDD)/R; No. 5= modified Temel and Adams= NV*MDD)/(R*H); No. 6= A; No. 7= DA/H; No. 8 = RA/(H*R*2); No.9=SLA/NS; No. 10= SLA/H; No. 11=A/NS; No. 12=A/NV.

Date	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12
			ft		ft^{-1}	degrees	ft		ft^2	ft	degrees	degrees
08/18/09	1.33	1.96	8.18	225.34	63.03	51.56	0.34	59.47	7.06	1.97	51.56	103.11
01/14/10	1.05	1.07	1.93	32.20	4.90	7.96	0.26	9.71	5.78	0.44	15.93	23.89
07/23/10	1.00	1.01	0.60	10.70	1.13	3.59	0.22	5.81	1.71	0.09	7.18	3.59
08/16/10	1.01	1.01	0.32	4.94	0.49	4.31	0.17	4.24	1.68	0.06	12.94	4.31
10/25/10	1.00	1.00	0.27	3.98	0.38	1.48	0.16	4.14	1.26	0.04	4.45	1.48
01/27/11	1.01	1.00	0.25	3.10	0.30	3.31	0.15	3.23	0.59	0.06	3.31	3.31

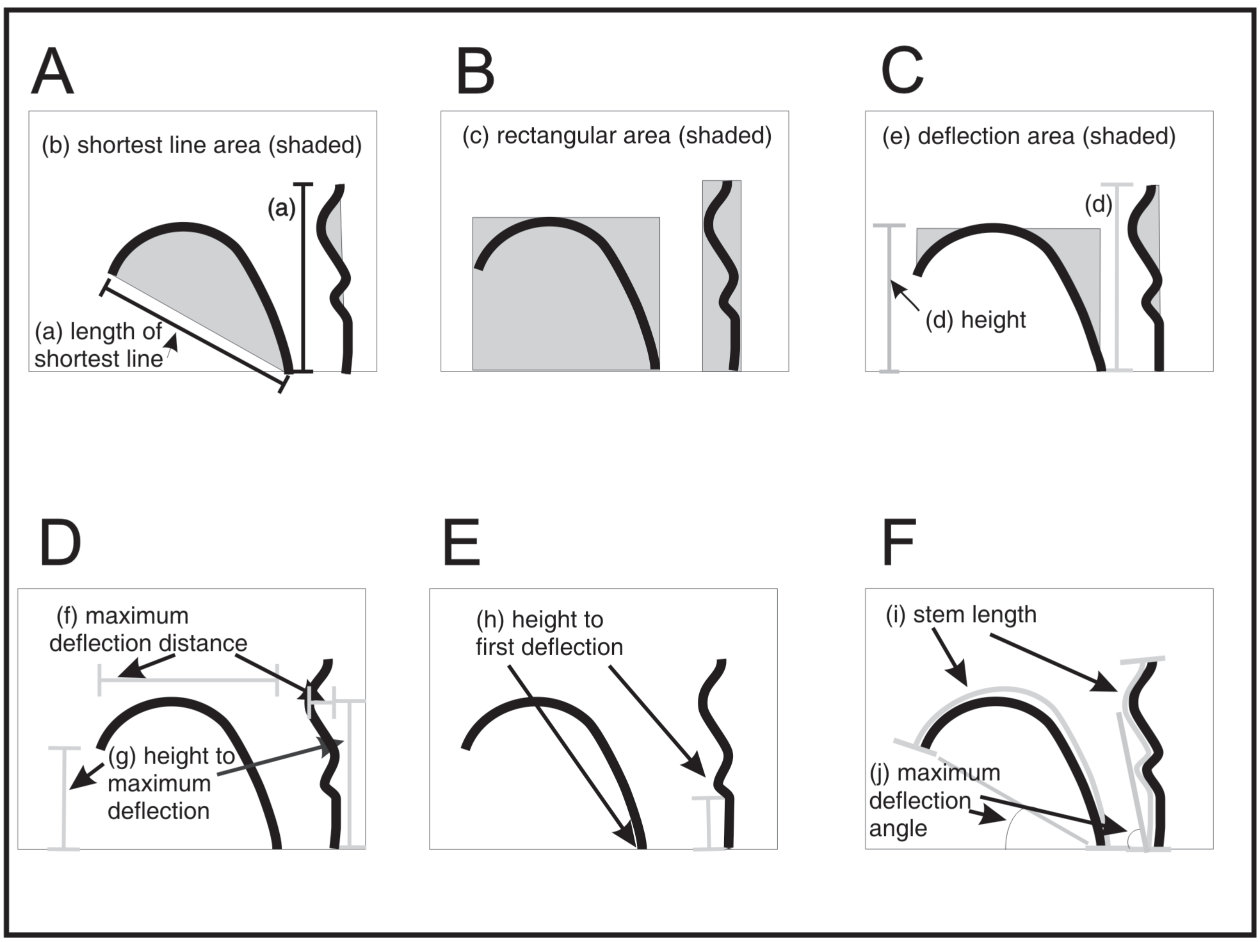

Figure 1—Diagram of the measurements taken on sample trees. Each of the six panels (A-F) contained two trees. The actual measurements are identified by lowercase letters (a-j). Measurements l and k are numbers of separated areas in A and C, respectively.

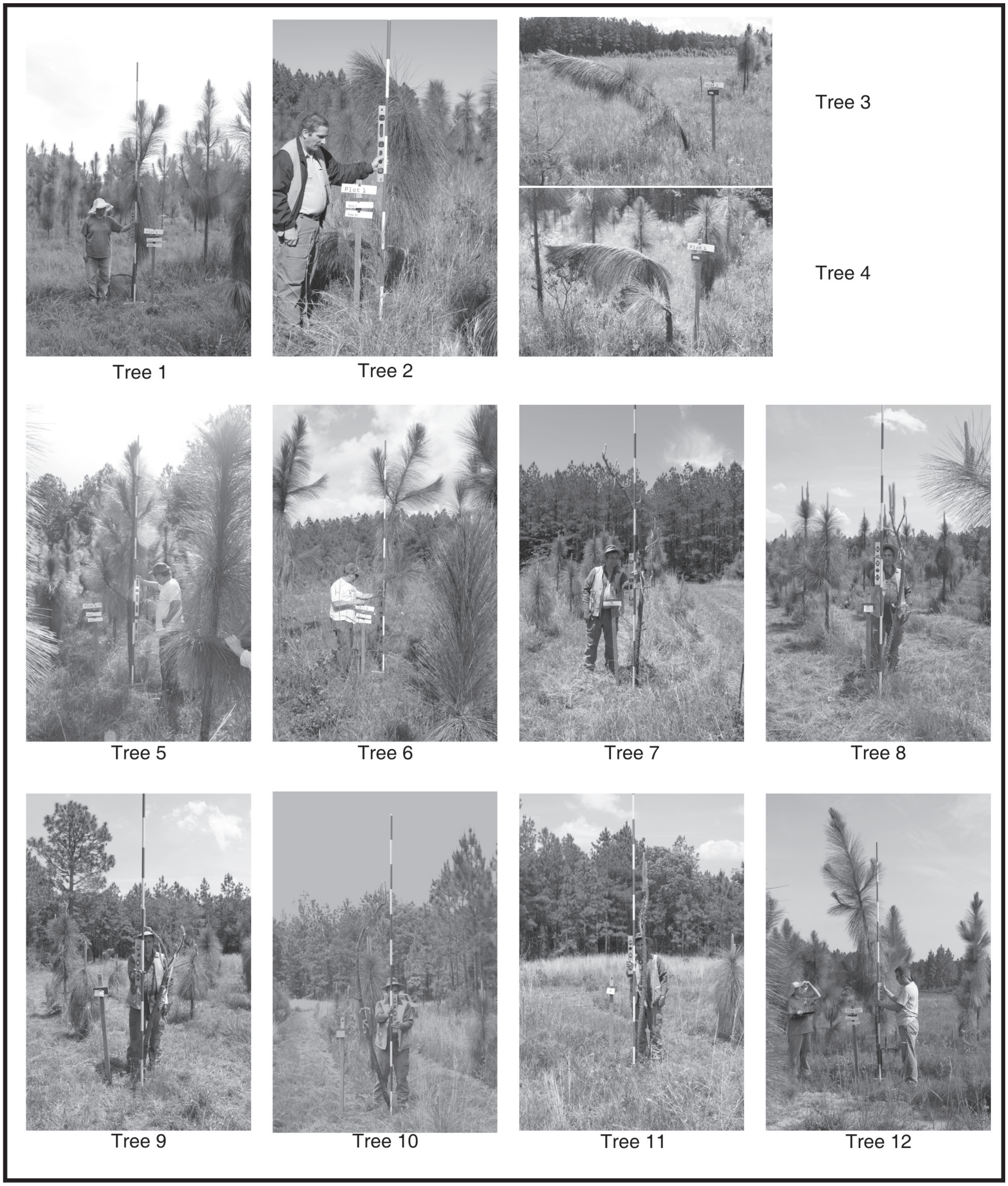

Figure 2—Photographs of the twelve longleaf pine saplings in the beginning of the sixth growing season. Stem deformity of these saplings were ranked subjectively and objectively. Note that trees 7 through 11 were stripped of needles for further analysis.

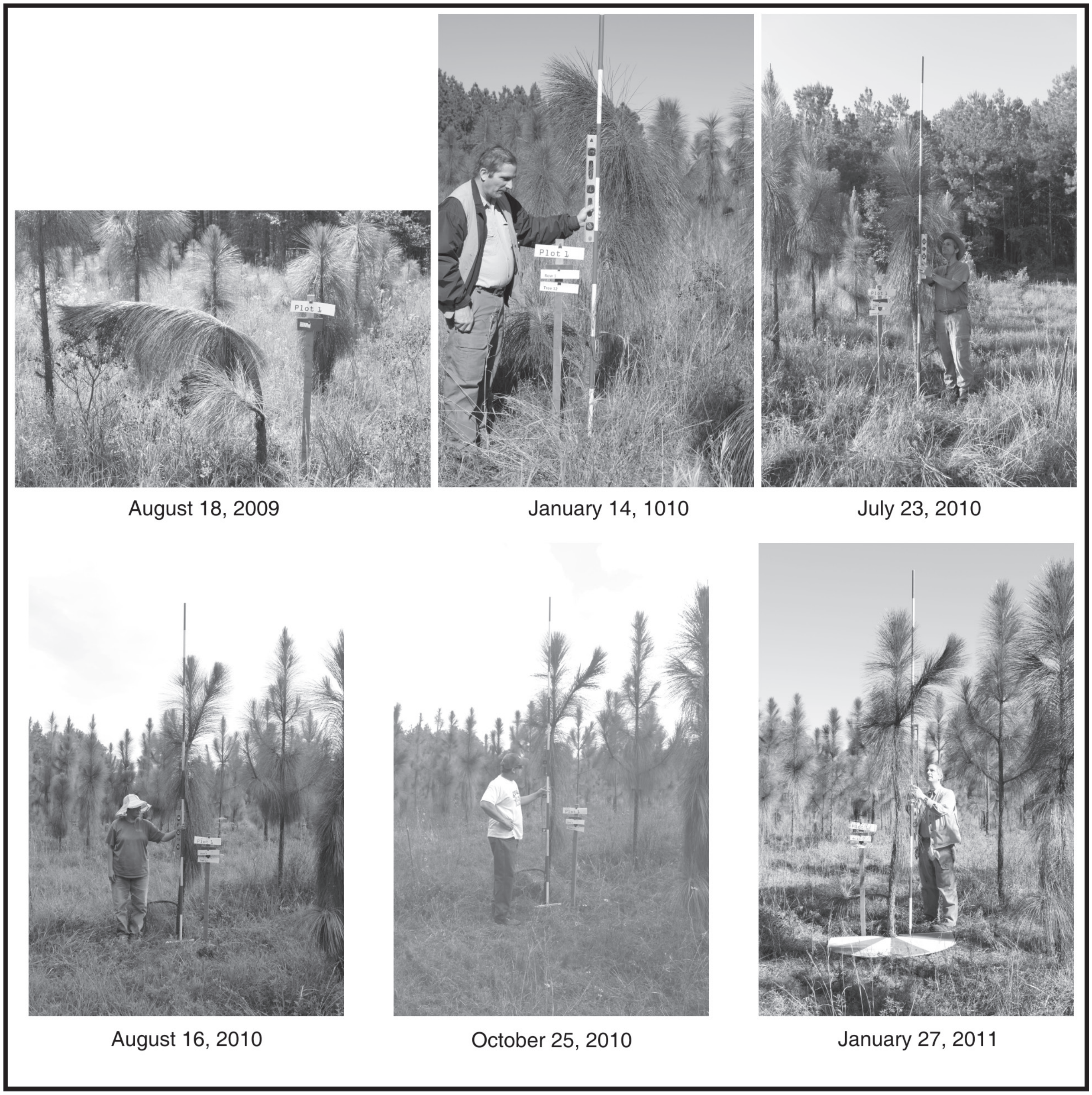

Figure 3—Photographs of the same longleaf pine sapling taken through time to show the recovery from stem displacement.