Arboricultural Journal

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--Manuscript Draft--

Full Title:	Supporting failure? Damage inflicted to establishing trees in London by a range of tree support and protection systems
Manuscript Number:	TARB-2017-0019
Article Type:	Research Papers
Keywords:	tree establishment; tree planting; tree protection; tree support; urban forestry
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Title Page

Supporting failure? Damage inflicted to establishing trees in London by a range of tree support and protection systems

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Abstract

Urban foresters employ a diverse range of different tree support and protection systems (TSPS) to help trees establish in the urban environment; however, in some cases, TSPS can cause damage to their host trees.

A survey was undertaken of 762 establishing trees across fourteen London boroughs to determine which types of TSPS are in current use, to assess how different systems perform and to record the frequency and severity of damage to trees associated with these different types and configurations of TSPS.

We found that TSPS-associated damage was highly prevalent within the sampled population, affecting 34.8% of the trees surveyed. Failure to remove TSPS components after the establishment phase was responsible for more than 80% of the cases of severe damage to trees found by this survey.

A comparison between the performance of several TSPS configurations in terms of their effectiveness and association with different TSPS damage types identified that the “two posts and ties” system performed consistently well in comparison with all other TSPS assessed. The survey data also highlighted a 35% rate of TSPS-associated damage related to the use of protective structures and that severe girdling damage and the development of adverse stem taper was more frequent when a TSPS incorporated the use of rubber spacers.

We conclude that some simple changes to current tree planting practice would help to minimize the impact of TSPS-associated damage in our urban forests.

Key words: tree establishment; tree planting; tree protection; tree support; urban forestry

Introduction

Successfully establishing trees in the modern urban environment can be a challenging task and it is common for high failure rates to be observed during the first few years after the initial planting process is completed (Gilbertson & Bradshaw, 1985; Nowak *et al.*, 1990; Lu *et al.*, 2010; Roman & Scatena, 2011). This propensity for a high rate of tree failure is understandable given the wide range of biotic and abiotic stress factors that urban trees are subjected to, with issues such as low-quality and anaerobic soils, soil compaction, impermeable surfaces, reflected heat, vandalism, transplant shock, drought, vehicle strikes and pollution, all acting to debilitate recently transplanted trees (Nowak *et al.*, 1990; Harris, 1992; Day & Bassuk, 1994; Arnold & Gibbons, 1996; Roberts *et al*, 2006; Urban, 2008; Hirons & Percival, 2012). Consequently, ensuring that new urban trees establish successfully and develop into viable, healthy mature individuals necessitates careful consideration of location, species and cultivar selection, mature tree size, planting specification and an associated maintenance programme (Clark *et al.*, 1997; Gilman & Sadowski, 2007; Urban, 2008; Watson & Himelick, 2013).

The planting specification will often include provision of a tree support structure, designed to provide the temporary mechanical support needed to keep the newly-planted tree upright, as well as provide stability to the rootball to allow development of the roots required for anchorage, hydraulic function and nutrient uptake (Wrigley & Smith, 1978; Appleton *et al.*, 2008; Alvey *et al.*, 2009; Hirons & Percival, 2012). Practical approaches to delivering this support requirement are diverse, incorporating single or multiple staking, wire-based guying systems or the use of underground guying (Harris *et al.*, 1974; Bradshaw *et al.*, 1995; Appleton *et al.*, 2008). In many cases, these tree support systems also incorporate protection features designed to defend the tree from physical damage, such as metal cages (Bradshaw *et al.*, 1995; Alvey *et al.*, 2009).

There is significant variation in the tree support and protection systems (TSPS) used in urban environments. The choice of TSPS is influenced by many factors, including: different site requirements and constraints, the extent of planting and maintenance budgets, the experience of urban foresters and other professionals involved with the tree planting process and the wide range of different commercial products available (Alvey *et al.*, 2009; Hirons & Percival, 2012). Disagreement within the urban forestry community on how to best stabilize a newly-planted tree has been suggested as a factor in the popularity of so many different systems (Appleton *et al.*, 2008). For example, the authors are surprised that any practitioners still use wire tree ties, as the frequency and level of damage to trees established with them, from our experience, is often high and severe (Fig. 1).

Insert Figure 1 near here

A general absence of published research on support system performance has been highlighted (Appleton *et al.*, 2008); this is perhaps due to other tree establishment issues (*e.g.* available soil volumes) being considered more significant (Nowak *et al.*, 1990). In spite of this shortfall in data, there are some studies that provide urban foresters with insight into the merits and failings of aspects of TSPS. These studies include an investigation into the effectiveness of different TSPS to wind loading (Eckstein & Gilman, 2008) and the effect of staking height on tree growth characteristics and stem taper (Leiser, & Kemper, 1968; Harris *et al.*, 1974; Svihra *et* *al.*, 1999).

This quantitative data on TSPS performance is supplemented by information that consolidates anecdotal observations on the positive and negative aspects of different TSPS configurations, components and management practices (Harris, 1992; Bradshaw *et al.*, 1995; Hirons & Percival, 2012; Watson & Himelick, 2013).

There is considerable disparity within these texts on the best approach to TSPS configuration, with several sources questioning their effectiveness or citing their capacity to cause damage to the trees they are meant to support and protect. Injuries to trees caused by TSPS include mechanical injury, deformation and arrested stem and/or root development (Eckstein & Gilman, 2008; Urban, 2008; Watson & Himelick, 2013).

Four main categories of TSPS damage are commonly identified within arboricultural texts: abrasion damage, girdling damage, occlusion damage and the development of adverse stem taper (Harris, 1992; Bradshaw *et al.*, 1995; Urban, 2008; Watson & Himelick, 2013).

Abrasion damage is the result of friction caused by an unwanted rubbing contact between the tree and TSPS components (Bradshaw *et al.*, 1995). Figure 2 demonstrates severe abrasion damage, which can cause significant injury to the tree's inner bark and vascular tissues and lead to dysfunction and disease ingress.

Insert Figure 2 near here

Girdling damage occurs when an object (typically a tree tie) encircles a stem or branch (Fig. 3). As the tree thickens through the process of secondary growth, a girdling object can disrupt cambial growth, potentially leading to stem malformation, significant dysfunction and, in some cases, strangulation or structural failure (Nowak *et al.*, 1990; Watson & Himelick, 2013). Girdling of stems most commonly develops if tree ties are initially installed too tightly or left in place beyond the period of establishment (Bradshaw *et al.*, 1995).

Insert Figure 3 near here

Occlusion damage follows prolonged unwanted contact between a tree and a foreign object (Fig. 4). Over many months and years, secondary growth can slowly envelop the object and in advanced cases can absorb it completely (Bradshaw *et al.*, 1995; Lonsdale, 1999).

Insert Figure 4 near here

Providing adequate support for establishing trees is dependent on striking a balance between limiting root-ball movement to ensure successful root-soil coupling and allowing a degree of stem flexure to encourage sufficient reactive strengthening of the stem (Bradshaw *et al.*, 1995; Watson & Himelick, 2013). Adverse stem taper (AST) is a problem associated with instances where trees are over-supported in the tree nursery or during establishment and such trees are thus deprived of the normal stem motion (NSM) required to stimulate normal stem development (Leiser, & Kemper, 1968; Svihra *et al.*, 1999).

In an unrestricted tree, the reactive strengthening process of thigmomorphogenesis acts to thicken stems, equipping them with the required physical strength for self-support and the resilience to survive strong wind events and other external forces (Telewski & Jaffe, 1986). Visual evidence of TSPS-induced disruption to the thigmomorphogenesis process is manifested in the loss of natural taper to a young tree's stem, where the taper can be observed to be significantly reduced, or in advanced cases becomes adverse (Fig. 5), signifying an over-supportive TSPS, the development of a structural weakness in the stem and an increased chance of mechanical stem failure (Burton & Smith, 1972; Svihra *et al.*, 1999).

Insert Figure 5 near here

Most TSPS damage takes several years to develop to an advanced state and if identified early, can be quickly and easily remedied (Lonsdale, 1999; Watson & Himelick, 2013). It is therefore advised that establishing trees are visited frequently as part of an on-going maintenance programme to reduce the risk of TSPS damage (Patch, 1987; Lonsdale, 1999). Furthermore, TSPS-associated damage is likely to be considerably exacerbated if TSPS remain in place beyond the period necessary for successful tree establishment (Appleton *et al.*, 2008).

Although many sources advocate the removal of TSPS components within one to two years following planting (Bradshaw *et al.*, 1995; Gilman & Sadowski, 2007; Urban, 2008; Hirons & Percival, 2012), there is evidence that TSPS are often left on for much longer periods. In a survey by Appleton *et al.* (2008), 71% of urban foresters had observed damage resulting from TSPS being left on for too long.

Current quantitative data on TSPS damage is limited to visual assessment information gathered as part of tree mortality surveys and audits, some of which are now quite dated (Foster & Blaine; 1978; Gilbertson & Bradshaw, 1985; Nowak *et al.*, 1990). A dedicated study on TSPS-associated damage to trees is desirable to identify the common types of damage, the frequency of that damage and whether some systems cause more or less of such damage than other systems.

In addition, the increasing popularity of TSPS as a standard approach to urban tree establishment (Alvey *et al.*, 2009), in the face of falling local authority maintenance budgets in the UK (NAO, 2014), combined with greater public, corporate and political interest in new tree planting (Zhang *et al.*, 2007), could be acting to exacerbate the problem of TSPS-associated damage to trees. Could it be the case that the use of cheaper TSPS is resulting in a higher frequency of damage to newly-planted trees?

In this study, a sample of London's establishing trees were surveyed to determine common TSPS in current use and to assess their performance in terms of the support provided, the extent of normal stem motion (NSM) they allowed and the frequency and severity of any TSPS-associated damage to these trees. It is hoped that findings from this study can enable urban tree managers to make more informed choices when specifying TSPS for tree planting specifications and when planning tree maintenance programmes.

Materials and Methods

Survey area

This study was conducted across fourteen central London Boroughs: Camden, Greenwich, Hackney, Hammersmith & Fulham, Highbury & Islington, Kensington & Chelsea, Lambeth, Lewisham, Newham, Richmond, Southwark, Tower Hamlets, Wandsworth and Westminster.

Data collection

Field data was collected between December 2016 and February 2017, with survey areas selected within each borough using a process of stratified random sampling. Aerial photography and online street mapping were used to shortlist several locations within each borough that contained establishing urban trees in public spaces. One of these shortlisted locations was then selected by a dice roll to be surveyed. All establishing trees with TSPS in place and within 500 metres of the randomly-selected location were surveyed, unless the trees were inaccessible or unsafe to survey (*e.g.* trees were omitted that were fenced off in an area directly adjacent to a railway line or similar hazard). No distinction was made between publicly and privately-owned trees. This process of random site selection was carried out for all fourteen London boroughs involved in this survey.

Measurements taken

Each tree was assigned a unique reference number and the tree’s height class, genus and stem diameter at 1.5 metres (DBH) was recorded. The location characteristics were assessed based on the amount of open soil surface surrounding the tree. This characterization incorporated four categories: Street or paved areas, grass verges or small open soil areas of up to 10 m^2, medium-sized open areas of between 11 to 20 m^2 and larger open spaces and parks in excess of 20 m^2 in size.

Information on each TSPS was gathered including the configuration, quantity and component material of all posts, straps and spacers. The height of the attachment point of any straps on the tree's main stem was measured. The height, material and arrangement of all protection structures were also recorded and all TSPS were photographed.

Assessing support provided and normal stem motion

An evaluation was made of the support system's performance for each tree, based on individual assessment of the support provided and the extent that the TSPS allowed normal stem motion (NSM) by manipulating the tree's stem. Each tree was assigned a numerical score for these two characteristics, based on the scales presented in Tables 1 and 2.

Insert Table 1 near here

Insert Table 2 near here

The survey included a simple assessment of the status of each tree in terms of whether it was 'established' and thus removal of the TSPS was overdue. Only trees that displayed extensive crown development and a substantial increase in DBH since their planting were recorded as ‘established’, with all other trees recorded as ‘not yet established’.

Assessing TSPS-associated damage

An assessment was made of each tree in terms of the presence and severity of four different TSPS-associated damage classifications: abrasion, girdling, occlusion and the development of adverse stem taper (AST). All incidences of TSPS-associated damage were recorded and photographed. Each tree was subject to a thorough visual assessment and was subsequently assigned a numerical score for each damage classification based on the scales presented in Tables 3 to 6.

Insert Table 3 near here

Insert Table 4 near here

Insert Table 5 near here

Insert Table 6 near here

Statistical analysis

Survey data was not normally distributed and involved assessment of seven different TSPS, so non-parametric tests were used to determine any statistically significant findings.

To determine where there were differences in performance between TSPS, or component parts of such systems, and the associated damage to trees, Chi Square tests were used. Equivalence tests were used to determine if mean scoring was higher or lower for some types of TSPS-associated damage. Ordinal regressions allowed for analysis to find any significant relationships between measured parameters and categorical data.

All statistical analysis was undertaken using Minitab v. 18.

Results

Trees surveyed for this study

In total, 762 establishing trees were surveyed across fourteen London boroughs for this study. 45.9% of the total survey group were located in streets or growing within paved areas, 15.5% were found in grass verges or small landscape areas up to 10 m^2 in size, 14.4% were located in open areas of up to 20 m^2, and 24.2% were located in larger open spaces and parks.

The survey data incorporated information on 49 different tree genera. The most frequent genus encountered was *Prunus* at 13.8% of the sample surveyed, followed by *Betula* at 10.0% and *Sorbus* at 9.8%. The top ten most frequently encountered genera made up 70% of the trees surveyed (Fig. 6).

Insert Figure 6 near here

Tree size

35.8% of the sample was made up of trees estimated to be less than three metres tall, with a majority (59.8%) being categorised as of medium height (3- 6 metres). Only 4.4% of the surveyed sample was found to be over six metres in height.

Support systems

Eight distinct categories of tree support systems were identified during the survey (Table 7).

Insert Table 7 near here

The seven most recorded categories were then assessed for their frequency of TSPS-associated damage and rated for their support and how much they allowed normal stem movement. Unfortunately, there were too few instances of integrated metal structure and tie systems to carry out statistical analysis on this support type.

Protection systems

Within the sample surveyed, 51.7% of the trees had some form of protective structure associated with them. Six categories of protection system were identified from the survey data (Table 8).

Insert Table 8 near here

The three most recorded categories of protective structures (budget cages, premium metal guards and integrated metal guards) were statistically analysed for their association with TSPS-related damage.

TSPS-associated damage to trees

Of the 762 trees surveyed, 262 specimens (34.8%) were found to have one or more instances of TSPS-associated damage: 66.8% of this damage was rated as of low severity, having been given scores of 1-2 and 15.27% were classified as high, rated as 4-5 on the associated scales (Tables 3-6).

Damage classification

Table 9 details the number of incidences of each TSPS damage classification identified within the sample.

Insert Table 9 near here

Abrasion damage was the most prevalent TSPS-associated damage type and the most damaging, with nearly half (48.3%) of all incidences being classed as moderate to severe and 15.4% being classified as advanced to severe. It was also the only TSPS-associated damage classification to attract the maximum damage rating of five, which was recorded for thirteen trees in this study (Fig. 7).

Insert Figure 7 near here

Adverse stem taper (AST) was the second most prevalent TSPS-associated damage type. However, instances of this type of damage were comparatively minor when compared with other forms of damage, with 77.8% of incidences of AST being rated as mild and only 1.6% of cases being rated as advanced or severe.

Although only slightly fewer cases of girdling damage were observed than AST, girdling damage tended to be more serious within the sampled trees, with 36.2% of cases being rated as moderate, advanced or severe. Girdling damage also exhibited the second highest rating of advanced to severe damage (10.34%).

Occlusion damage was far less prevalent than other TSPS-associated damage types and damage severity was generally mild to moderate with 85.7% of cases rated at two or three and severe damage (scores of four) accounting for only 7.24% of this damage type.

Table 10 records the causes of the TSPS-associated damage in the sample population of trees. The most frequent cause of damage was contact with protection structures, which was observed on more than half of all damaged trees (53.8%). Note that some trees exhibited damage from more than one cause, hence the counts for damage in Table 10 exceeds 100% of the trees noted as damaged.

Insert Table 10 near here

TSPS types and associated damage

Figure 8 illustrates how the causes of damage were distributed for the TSPS types surveyed.

Insert Figure 8 near here

Statistical relationships in the collected data

A Chi Square test identified that there were significant differences in the rates of TSPS-associated damage with different tree support systems ($X^2_7 = 187.32$; $p < 0.001$). Table 11 provides the data used for this statistical test.

Insert Table 11 near here

Table 12 provides a summary of TSPS performance across each damage assessment category. It also summarizes the severity ratings of that damage by presenting the percentages of those that were rated high (ratings of 4 or 5) and low (ratings of 1 or 2).

Insert Table 12 near here

Angled post and ties

This system recorded the highest overall rate of abrasion damage (82.9%) and occlusion damage (31.91%). It ranked moderately in terms of AST and girdling damage. However, it provided a good range of support and NSM, outperforming both single-post-and-tie and double-post-and-crossbar in these two assessments.

Double post and crossbar

This system was associated with high levels of detrimental post contact (28.2%) and too tight tree tie contact (30.7%), meaning it recorded the second highest incidence of abrasion damage overall. This TSPS was also responsible for the highest frequency of girdling damage of any TSPS, although 70% of this damage was classified at a ‘low’ rating (scores of 1 or 2).

This TSPS had the highest rate of AST within the sample; however, 81.8% of this damage was categorised as being of low severity. This TSPS also displayed the highest percentage of low support ratings (7.7%) and the smallest percentage of high NSM scores (23.1%).

Double post and ties

This system was consistently among the lowest for every damage classification. Severity of any TSPS-associated damage also tended to be low for this TSPS. It was middle ranking in terms of support rating; however, it significantly outperformed both double-post-and-crossbar and single-post-and-tie systems. This system also scored highly for NSM, with 73.0% of specimens with this TSPS rated as high for the extent of stem movement allowed by this system.

Single post and tie

This system was middle-ranking for abrasion and girdling damage but second highest for AST. It was the only TSPS to exhibit high severity occlusion damage in this survey. The mean scores for support and NSM with this type of TSPS were significantly lower than the double-post-and-tie system, as determined by two sample equivalence tests (Support: $T_{1,207} = 2.6419$; $p < 0.004$; NSM: $T_{1,133} = 3.4357$; $p < 0.001$). This TSPS type also exhibited the highest proportion of low scores for NSM (18.92%).

Figure 9 illustrates that this TSPS type had a much higher incidence of damage arising from detrimental tie contact than post or cage contact.

Insert Figure 9 near here

Triple post and ties

This system was middle-ranking in terms of the frequency of abrasion damage, which affected a third of all trees in this classification. Abrasion damage was generally mild with 72.7% of the incidences rated low and none rated as severe.

This system attracted the second highest frequency of girdling damage (18.2%), but was free of cases of occlusion and AST. It attracted the second highest mean rank score for support rating with 81.8% of cases rated as high. It was middle-ranking for its NSM rating.

Underground guying systems

This TSPS was associated with extremely high levels of abrasion damage (71.0%), a sizeable proportion of which were of high severity (18.2%). Figure 10 shows a typical example of abrasion damage on a tree supported by underground guying, with the tree's stem coming into contact with an integrated metal protective structure.

Insert Figure 10 near here

Aside from this high incidence of abrasion damage, no other forms of TSPS-associated damage were recorded for this TSPS. A support rating was not given for this TSPS as it was located underground and consequently was not visible to be assessed. However, this system attracted the highest scores for NSM with 87.1% of the instances of this TSPS rated as high for this factor.

Damage associated with protective structures

Of the 762 surveyed trees, 394 (51.7%) had some sort of protective structure in place. 35.0% of all trees that had a protective structure installed were suffering some degree of damage arising from detrimental physical contact with it (*e.g.* Fig. 10).

TSPS-associated damage was present for 36.7% of budget metal cages, 20.5% of premium metal guards and 65.2% of integrated metal structures. A Chi Square test identified these differences in damage incidences to be significant ($X^2_3 = 43.327$; $p < 0.001$).

Overdue removal of TSPS components

Cases where the planted trees were well-established and TSPS removal was considered overdue made up 25.7% of the surveyed trees and accounted for 47.7% of all damaged trees. Where the TSPS was not identified as due for removal, 24.3% of these trees were damaged ($n = 571$) – where the TSPS was identified for removal, 66.0% of these trees were damaged ($n = 191$). A Chi Square test for association found this proportional difference to be significant ($X^2_1 = 109.33$; $p < 0.001$).

Removal of TSPS was overdue in 50% of cases of damage arising from tie contact, 52.9% of cases of protection structure contact, and 41.5% of cases of post contact. Retention of TSPS for post-establishment trees was associated with more severe damage in each classification: Removal of TSPS was overdue in 80.6% of the cases of severe abrasion damage, 83.3% of the cases of severe girdling damage, 100% of the cases of severe occlusion damage and 100% of the severe cases of AST.

Figure 11 illustrates the average severity of damage to trees where TSPS removal was overdue in comparison with all other establishing trees surveyed, for the four damage categories used in this study.

Insert Figure 11 near here

Supporting this finding further, analysis also found that 24.9% of trees in the small height class were damaged by TSPS, 38.4% in the medium height class and 66.7% in the large height class. A Chi Square test identified that there was significantly less TSPS-associated damage occurring to trees in the smaller height class and a significantly higher proportion of larger trees exhibited TSPS-associated damage ($X^2_1 = 18.26$; $p < 0.001$).

Relationships between support height, normal stem motion and adverse stem taper

An ordinal regression identified that the ratings for NSM were statistically associated with the severity of AST damage, in that specimens with lower ratings for normal stem motion were more likely to have developed adverse stem taper, with AST severity linked to the NSM rating ($Z_{4, 580} = 5.29$; $p < 0.001$).

There was no significant relationship found between attachment height and the rating for NSM, suggesting that the support system type was a much more important factor than the height of attachment to the tree's stem.

Use of spacers and TSPS-associated damage

TSPS with spacers accounted for 46.3% of the support systems assessed. 30.8% of trees were affected by TSPS-associated damage when spacers were present, compared to 26.1% of trees without spacers being damaged. TSPS with spacers accounted for 78.7% of all cases of AST damage. AST damage in those trees with spacers fitted was also more severe, on average, with 27.1% of incidences classified as moderate to high compared to only 7.7% of incidences in the rest of the sample classifying as that severe. Spacer use had a similar effect on rates of girdling damage: TSPS with spacers accounted for 78.2% of all cases of girdling damage. However, a higher percentage of severe girdling damage was recorded when spacers were absent.

Rates of abrasion damage were similar between TSPS with spacers and those without spacers, with 71 cases of abrasion damage with no spacers used and 64 cases where spacers had been used. Looking in more detail at the causes of abrasion damage, it is apparent that damage derived from post contact made up a far greater proportion of the damage in the absence of spacers, accounting for 65.7% of the total abrasion damage as opposed to just 9.5% where spacers were present. In contrast, abrasion damage arising from contact with ties was 31.8% of all abrasion damage when spacers were present, as opposed to only 2.9% in the absence of spacers.

The differences in the level of damage to trees between those TSPS with spacers and those without is illustrated for all damage classifications in Figure 12.

Insert Figure 12 near here

Spacers, support, and normal stem motion

Those trees without spacers as components of their TSPS attracted a higher mean NSM rating (3.856 ± 0.0395 Standard Error (SE)) than those using spacers (3.638 ± 0.0509 SE). A Two Sample Equivalence Test identified that these means were significantly different ($T_{1,537} = 3.3838$; $p < 0.001$), showing there was more normal stem motion in TSPS without spacers as components.

Discussion

TSPS-associated damage

TSPS-associated damage was a considerable problem for trees in the study area, affecting more than a third of the trees surveyed.

A large proportion of the damage was low in severity (66.8%), which is encouraging as trees with minor TSPS damage can recover from their injuries following remedial alterations to the TSPS (Bradshaw *et al,* 1995). However, 15.3% of the damaged trees displayed more severe damage and the sort of injuries that are likely to considerably limit lifespan or cause long-term deformations in the trees (Lonsdale, 1999). Making up 5.5% of the total trees surveyed, the high-rated damage found by this survey constitutes a considerable loss of expenditure and future amenity.

Types of damage

Wounds created by abrasion damage can be extremely problematic to developing trees as injuries of this nature can increase the chance of disease and decay ingress (Boddy & Rayner 1983; Strouts & Winter, 1994; Jones & Baker, 2007; Brasier, 2008; Schwarze, 2008). It is therefore important to note that abrasion damage was the prevalent damage type associated with TSPS, mostly caused by contact with posts or protective cages.

Adverse stem taper and girdling damage each affected nearly a quarter of the damaged population and 8% of all the trees surveyed. The association between these damage types and severe malformation or tree failure means that their occurrence at this frequency should be considered a real cause for concern (Lonsdale, 1999).

However, although still undesirable, the high percentages of low severity AST damage recorded can be considered to be encouraging as, following removal of all movement restrictions, young trees tend to recover from mild AST over time (Watson & Himelick, 2013). Conversely, the 10% of cases of girdling damage rated as high in severity are likely to have longer-term implications, as even after the girdling objects are removed, severely damaged trees are left vulnerable to mechanical failure (Bradshaw *et al.*, 1995).

Occlusion damage requires an extended period of contact between an object and the tree in order for it to develop (Bradshaw *et al.*, 1995). Although rates of occlusion were low in the sample, the fact that it was observed at all suggests that a lack of timely removal of TSPS components is a significant problem within the wider tree population.

Post-establishment retention of TSPS

Failing to remove TSPS components after the establishment phase was found to have a considerable impact on both rates and severity of TSPS-associated damage.

More than a quarter of the trees surveyed were found to have TSPS components still in place after establishment had been completed. The effect of this on the frequency and severity of TSPS damage was dramatic, with cases where TSPS removal was overdue making up nearly half of the total damage caused and accounting for more than 80% of the cases where the damage to trees was judged to be severe.

These findings identify that lack of timely maintenance is contributing to TSPS-associated damage and demonstrate how a more consistent and proactive approach to TSPS removal could yield a dramatic decrease in both the frequency and severity of this type of damage across the urban forest.

The necessity for regular maintenance visits and timely removal of TSPS components has been widely publicized in many arboricultural textbooks and reference materials (Gilbertson & Bradshaw 1985; Patch, 1987; Harris, 1992; Bradshaw *et al.,* 1995; Lonsdale, 1999; Watson & Himelick, 2013). However, probably due to a number of factors, these actions were not being taken for a substantial proportion of these trees.

The recent adoption of an austere economic policy has had a significant impact on local authority budgets in London, with boroughs experiencing on average a twenty-seven per cent reduction in revenue between the financial years 2010-11 and 2015-16 (NAO, 2014). These budget reductions have led to a significant cutback in local authority spending on environmental services, leading to considerable job losses and dramatic reductions in operational budgets (NAO, 2014). This is one likely factor that explains the lack of maintenance exhibited and the TSPS-associated damage that subsequently occurred.

Furthermore, the increased pressure for new tree planting in London, driven by increased public and corporate interest in environmental issues (Zhang *et al.*, 2007), combined with ambitious mayoral targets for new tree planting in the capital, are likely to have put even more pressure on London’s already overstretched urban tree maintenance budgets. A drive for greater tree numbers without adequate provision for on-going maintenance has been shown to be problematic in other cities (Pincetl *et al.*, 2013) and it is likely that similar issues are now arising in London.

Although it is important to focus on reducing TSPS-associated damage directly through proactive maintenance programs and a more disciplined approach to removal of TSPS components once young trees are successfully established, it is also critical to anticipate likely constraints on tree management. In this study, by comparing the performance of different TSPS configurations and component materials, we have identified planting practices that reduce instances of TSPS-associated damage.

Performance of different TSPS

Making up 52.5% of the survey group, the popularity of the double post and tie system suggests many urban foresters see merits in this support system. Our comparison of TSPS performance demonstrated that this popularity is warranted: this support system performed consistently well, having the least likelihood of TSPS-associated damage of the seven systems assessed by this study (Fig. 9). Although the two post and tie system has attracted some criticism for offering inferior levels of support (Eckstein & Gilman, 2008), this configuration comprehensively outperformed the second most popular system, single post and tie (19.3%) in every damage category. The single post and tie system was generally a ‘stiffer’ system, which led to more frequent development of AST. Single post systems also tended to have the post set near to the tree’s stem, leading to either abrasion damage or the use of spacers and subsequent loss of normal stem motion.

While these two TSPS types made up the majority of the trees surveyed, the data highlighted the popularity of a range of alternative systems such as underground guying, double posts and a crossbar and multiple staking systems. Although the data supported existing evidence that alternative systems can infer some advantages – such as a greater range of stem motion in underground guying systems – it also demonstrated that these configurations were more prone to TSPS-associated damage overall.

A number of factors potentially act in concert to explain this finding. In the case of underground guying, the better stem motion led to greater levels of damage to trees through more stem contact with protective cages. For other TSPS, it may be that the increasing complexity of these alternative systems increases the chance of detrimental contact with components. It could also be the case that alternative configurations may be more popular on privately-owned sites, which may be managed differently to those subject to the more uniform planting specifications and established maintenance programs of some local authorities.

It is important to note that these findings only offer a comparison between the systems currently in use and there is some evidence that other TSPS may confer some significant advantages (Eckstein & Gilman 2008; Watson & Himelick, 2013). The findings of this investigation should not act as discouragement for innovation in this field or be used as a justification for the adoption of a blanket approach to tree support, as some site constraints can make the adoption of alternative techniques and configurations advantageous (Eckstein and Gilman, 2008).

Protective structures

Contact with protective structures was the most frequent physical cause of TSPS-associated damage overall, affecting 18.5% of the trees surveyed and over half of all damaged trees (Table 10). Budget cages were responsible for more of this damage than premium protective guards. Solving this recurring problem would substantially decrease rates of TSPS-associated damage across the wider urban forest.

London is currently experiencing rapid rates of development (DCLG, 2015) and significant increases in population, with its population growing by 1.7 million in the last twenty years (GLA, 2015). The associated urban intensification and densification could lead to an increased likelihood of detrimental conflicts between urban activity and urban trees. Vandalism and accidental damage to trees has been shown to be a serious problem in some high-density urban areas (Jim, 1987). It is therefore unsurprising that urban foresters were found to have deployed protection structures on more than half of the trees surveyed in these London boroughs.

However, with more than a third of the trees fitted with a protection structure suffering damage from that structure, it may be that installing protection systems could be doing more harm than good. This dilemma could be informed by assessing the local rates of vandalism and accidental damage to urban trees, which have been recorded to be below 20% in some cases (Jim, 1987). However, Gilbertson & Bradshaw (1985) recorded tree mortality rates from vandalism alone to be 18%, suggesting that there may also have been a much higher rate of non-fatal vandalism to the trees in their study. Further study is recommended to investigate rates of accidental damage and vandalism on a comparable sample of London's trees, to better inform the tree protection strategies currently in use.

Rates of damage to trees can be affected by location characteristics such as pedestrian footfall, proximity to vehicular traffic and the socio-economic status of residents (Foster & Blaine, 1978; Nowak *et al.*, 1990; Lonsdale, 1999). However, in this study, the use of protective structures was found to be lowest in street or paved areas, which are likely to be at the highest risk of vandalism. This potentially indicates that some landscape architects and urban foresters may not be considering the site-specific risk of tree damage when prescribing tree protection structures and some may be adopting a blanket approach to their application within their specifications. Given the high rate of TSPS-associated damage observed in this study, a more targeted use of tree protection structures is advisable, only caging trees where it is proven necessary and where on-going management to deal with the threat of TSPS-associated damage can be assured. If underground guying is to be the principal support system, then additional components are needed to prevent swaying tree stems coming into contact with any associated metal cages or guards.

Attachment height, normal stem motion and AST

Adverse stem taper (AST) was closely associated with lower ratings for normal stem motion, and these, in turn, were related closely to TSPS consisting of single post systems or those using double posts and a cross-bar – both systems having spacers as a common component. It can be concluded that these stiffer forms of support are more likely to cause AST, especially if kept in place beyond the initial establishment period of one-to-two years.

Damage associated with the use of spacers

A spacer is a rubber block or strip that is used in some TSPS to prevent unwanted contact between posts or crossbars and the trees they support. Applied on single post systems or post and crossbar systems, they act as a buffer between wooden TSPS components and young tree stems (Bradshaw *et al.*, 1995). Strip spacers are also used on multiple stake systems with the aim of preventing unwanted post contact, providing extra support and improving visual appearance (Toms, 2017). Comment on the effectiveness of these components is almost entirely absent from associated literature.

Although TSPS with spacers made up less than half of the survey population they accounted for nearly 80% of all cases of AST and girdling damage overall. The survey showed spacers to be effective in preventing abrasion damage through post contact, but their addition led to a significant increase in abrasion via tie contact.

Spacers were associated with more rigid tree support systems (especially single post and tie and double post and cross-bar systems). As both AST and girdling damage are caused by restriction of the stem, it is likely that the more constricting hold of a tree tie with a spacer, as opposed to the open loop found on tree ties without spacers, is detrimentally constraining stem growth and movement in many cases.

Although spacer use remains essential on single post systems where a buffer is crucial to preventing significant abrasion damage (Bradshaw *et al.*, 1995), the use of strip spacers on multiple staking systems should be discouraged, as they are likely to increase the risk of TSPS-associated damage without providing a notable increase in support.

Conclusions and Recommendations

As an industry, we should share a collective sense of embarrassment that a problem as simple and preventable as TSPS-associated damage is so widespread and damaging within our capital’s urban forest. TSPS-associated damage constitutes a significant problem with a pressing need for prevention and mitigation. The impact of poor management on rates and severity of TSPS-associated damage is considerable and a more systematic and diligent approach to young tree maintenance is the best way to reduce its overall impact.

Based upon our findings, we would make the following recommendations:

- Stiffer support systems (angled post, single post, double post & crossbar, those incorporating spacers), if their use can be justified over the use of systems that allow for better stem flexure, should be kept in place for only a short establishment period.
- The use of protective structures, such as wire cages, comes with a risk of TSPS-associated damage, so their use should be limited to where such protection is considered essential.
- Protective caging should be generous in size and the system's design should anticipate normal stem motion and development of the establishing tree. Practitioners should note that the use of underground guying with narrow protective caging can lead to major stem abrasions during the establishment phase.
- The development of adverse stem taper can be avoided if the tree's stem is held in an open loop rather than confined by a tight strap or tie-and-spacer arrangement.
- Timely removal of TSPS components is critical in avoiding any severe damage occurring to establishing trees due to the presence of the TSPS.

By implementing the recommendations of this study, a significant amount of damage could be avoided and many trees saved from damage, dysfunction and possibly some early deaths too.

Acknowledgements

Our thanks go to Olivia Dryden who assisted with initial data collection.

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Word Count (including references): 8,498

Figure Captions

Figure 1: Damage caused to an establishing tree by a wire tree tie: the authors have extensive experience that these wire ties are highly prone to causing damage to the trees they are meant to support.

Figure 2: An example of advanced abrasion damage associated with a basic TSPS –

single angled stake and rubber tie support system.

Figure 3: This redundant TSPS is girdling its host tree, causing significant deformation of a secondary stem.

Figure 4: This tree has begun to occlude its own protection structure (in this case, a metal tree guard), following prolonged physical contact with it.

Figure 5: Prolonged over-support of the tree's stem by this single stake and tie has led to the development of adverse stem taper (AST).

Figure 6: Measurements were taken of all TSPS characteristics and their component parts in this randomized survey of establishing trees over fourteen London boroughs.

Figure 7: The top ten most frequently encountered genera in the 762 trees surveyed for this study.

Figure 8: Frequency of the five levels of TSPS-associated damage for the four damage categories: abrasion, girdling, occlusion and adverse stem taper. Low level damage was allocated a score of 1, severe damage a score of 5. In this study, only abrasion damage was found to have caused damage rated at level 5 to some of the establishing trees surveyed: all other damage was less severe.

Figure 9: The six main support systems found in this study causing TSPS-associated damage and the frequency of the four damage categories: abrasion, girdling, occlusion and adverse stem taper.

Figure 10: Abrasion stem damage to an establishing Ginkgo by an integrated metal tree guard. This tree has an underground guying system for its support, which allows considerable stem flexure – unfortunately, it is this freedom of stem movement that is leading to the damage shown.

Figure 11: A comparison of TSPS-associated damage between establishing trees and those considered overdue for TSPS component removal, for the four damage categories assessed in this study. The average severity rating for each damage category was calculated by summing all ratings for those with TSPS components overdue for removal (*n* = 191) and all other establishing trees surveyed (*n* = 571).

Figure 12: A comparison of TSPS-associated damage between TSPS with spacers and those without, for the four damage categories assessed in this study.

Table Captions

Table 1: Rating system for tree support used in this study.

Table 2: Rating system for normal stem motion (NSM) used in this study.

Table 3: Rating system for TSPS-associated abrasion damage used in this study.

Table 4: Rating system for TSPS-associated girdling damage used in this study.

Table 5: Rating system for TSPS-associated occlusion damage used in this study.

Table 6: Rating system for TSPS-associated adverse stem taper (AST) damage used in this study.

Table 7: The frequency of different tree support systems found by this study's tree survey, with counts of instances and the proportion of each system in relation to the total number of trees surveyed (*n* = 762).

Table 8: The frequency of different tree protection systems found by this study's tree survey, with counts of instances and the proportion of each system in relation to the total number of trees surveyed (*n* = 762).

Table 9: Frequency of the four damage categories for TSPS-associated damage to trees, with the proportion of each damage type as seen in the entire tree survey and as a proportion of all damaged trees.

Table 10: Breakdown of TSPS-associated damage into three categories, with counts and proportions in relation to all the trees surveyed and the damaged trees found.

Table 11: Summary of TSPS-associated damage instances for the eight different support systems found to be used in the surveyed trees (including no support system).

Table 12: Breakdown of TSPS-associated damage for the six most frequent support systems found in the surveyed trees, with counts and proportions of all four damage categories assessed in this study.

Table

Support Level	Rating	Description
No Support	0	The support system has failed and is offering the tree negligible or no support, leaving it in a condition where it is moving unsustainably, heavily tilted or already uprooted.
Poor Support	1	The support system is substantially underperforming, allowing significant visible movement of the root ball even under light loading. The uncontrolled movement of the tree is likely to act as a serious constraint to root development.
	2	The support system is underperforming. Although the system may be providing some support, it is allowing an undesirable extent of movement of the root ball under medium loading that could potentially prevent fine and structural root establishment.
Moderate Support	3	The support system is performing satisfactorily. There may be some slackening of components or a partial failure of the system, but adequate support is maintained. There may be some limited undesirable motion in the root ball, but this is unlikely to impose a significant constraint on healthy root development.
Good Support	4	The support system is in a good condition and is supporting the tree well, although there may be some slight slackening of posts or straps. There is no undesirable movement in the root ball even under heavy loading.
	5	The support system is in excellent condition and is providing good physical support of the rootball.

Table

Normal Stem Motion (NSM)	Rating for NSM	Description
Little to No Motion	0	The tree is held so firmly by its support system that there is effectively no stem movement at all. Natural stem development has been rendered impossible.
Poor Range	1	Very little stem motion is possible, the support system is detrimentally restricting movement to the extent that it is likely to act as a severe constraint to normal development of stem taper.
	2	Although some motion is possible, the tree is constricted in its movement to the extent that development of natural stem taper will be affected
Moderate Range	3	The support system is allowing a satisfactory range of stem motion, although a greater range of motion would be desirable. The development of the establishing tree may be affected by the restriction in its stem movement if this support system is left in place for too long.
Good Range	4	The support system is allowing a good range of stem motion. Although there may be some slight limitation in movement, the range of stem motion afforded by the support system is good enough to stimulate healthy development of stem taper.
	5	The support system is facilitating a normal range of stem motion.

Table

Abrasion Damage	Rating	Description
No Damage	0	No abrasion damage present.
Low Damage	1	Negligible damage. Superficial damage to temporary branches or undesirable contact between tree and potentially abrasive surfaces.
	2	Minor abrasion damage, including superficial bark damage to the main stem or primary structural limbs, moderate damage to lateral branches, or more advanced damage to temporary branches.
Moderate Damage	3	Moderate abrasion damage including bark damage or minor cambial damage inflicted on the main stem or structural limbs or more severe damage inflicted on temporary branches.
High Damage	4	Advanced abrasion damage, including damage to bark and vascular cambium on the main stem or significant cambial damage to primary structural limbs or lateral branches.
	5	Severe abrasion damage, including severe damage to the main stem and/or severe damage to primary structural limbs. Abrasive damage has been afflicted on significant areas of vascular cambium or has progressed beyond into xylem tissues

Table

Girdling Damage	Rating	Description
No Damage	0	No girdling damage
Low Damage	1	Object is applying undesirable pressure to stem, but current damage is superficial.
	2	Minor girdling damage. First signs of deformation are evident around the point of girdling but substantial damage has not yet been done
Moderate Damage	3	Moderate deformation of stem around a point of girdling. Stem is constricted and evidently deformed but not yet to a great extent.
High Damage	4	Advanced girdling damage. Girdling is causing serious constriction and deformation that threatens tree vitality, and girdling point is now a structural defect.
	5	Severe girdling of main stem, resulting in significant deformation and considerable vascular disruption. The girdling injury is highly likely to lead to stem death or mechanical failure.

Table

Occlusion Damage	Rating	Description
No Damage	0	No occlusion damage.
Low Damage	1	Superficial case of occlusion. Bark growth is only slightly disrupted around the object being occluded.
	2	Mild case of occlusion. Visible deformation of tissues around the object, but damage is still at an early stage. Removal of the occluded object is still possible.
Moderate Damage	3	Moderate case of occlusion. Occluded object is causing more serious deformation, although this is yet to progress to the stage where it is causing significant dysfunction or a distorted branch or stem form.
High Damage	4	Advanced case of occlusion, causing obvious deformation, dysfunction and/or a potential structural weakness.
	5	Severe case of occlusion, resulting in considerable malformation of the tree's stem. Occluded object embedded to the extent that mechanical failure of the tree's stem is made likely.

Table

Adverse Stem Taper Damage	Rating	Description
No Damage	0	Healthy stem taper
Low Damage	1	Neutral or superficially poor stem taper
	2	Mild adverse stem taper.
Moderate Damage	3	Moderate adverse stem taper. The stem is clearly underdeveloped below where it is supported and has undesirable stem morphology, although this may be less advanced. The stem retains some structural integrity
High Damage	4	Advanced adverse stem taper resulting in considerable deformation of the stem below its support system and a considerable reduction in structural strength of the stem has occurred.
	5	Severe adverse stem taper resulting in chronic malformation of the stem and a high risk of associated mechanical failure if the support system was removed.

Table

Support System Classification	Count	Percentage of All Trees Surveyed
Angled Post and Tie	47	6.17%
Single Post and Tie	147	19.29%
Double Post and Tie	400	52.49%
Double Post and Crossbar	39	5.12%
Triple Post and Ties	33	4.33%
Integrated Metal Structure and Ties	6	0.79%
Underground Guying	31	4.07%
Protection Structure Only	59	7.74%

Table

Protective structure	Count	Proportion of sample	Percentage of caged trees
Integrated Metal Cage	72	9.45%	18.27%
Premium Metal Guard	117	15.35%	29.70%
Budget Metal Cage	180	23.62%	45.69%
Fencing wire	19	2.49%	4.82%
Rabbit/ Strimmer Guard	4	0.52%	1.02%
Wood or organic guard	2	0.26%	0.51%
No Protection Structure	368	48.29%	

Table

Damage Type	Number of incidences of damage	Percentage of Surveyed Tree Population (*n* = 762)	Percentage of Damaged Trees (*n* = 262)
Abrasion	201	26.38%	76.72%
Girdling	58	7.61%	22.14%
Occlusion	28	3.67%	10.69%
AST	63	8.27%	24.05%

Table

Cause of Damage	Count	Percentage of all trees surveyed (*n* = 762)	Percentage of damaged trees (*n* = 262)
Tie Contact	96	12.6%	36.6%
Cage Contact	141	18.5%	53.8%
Post Contact	53	7.0%	20.2%

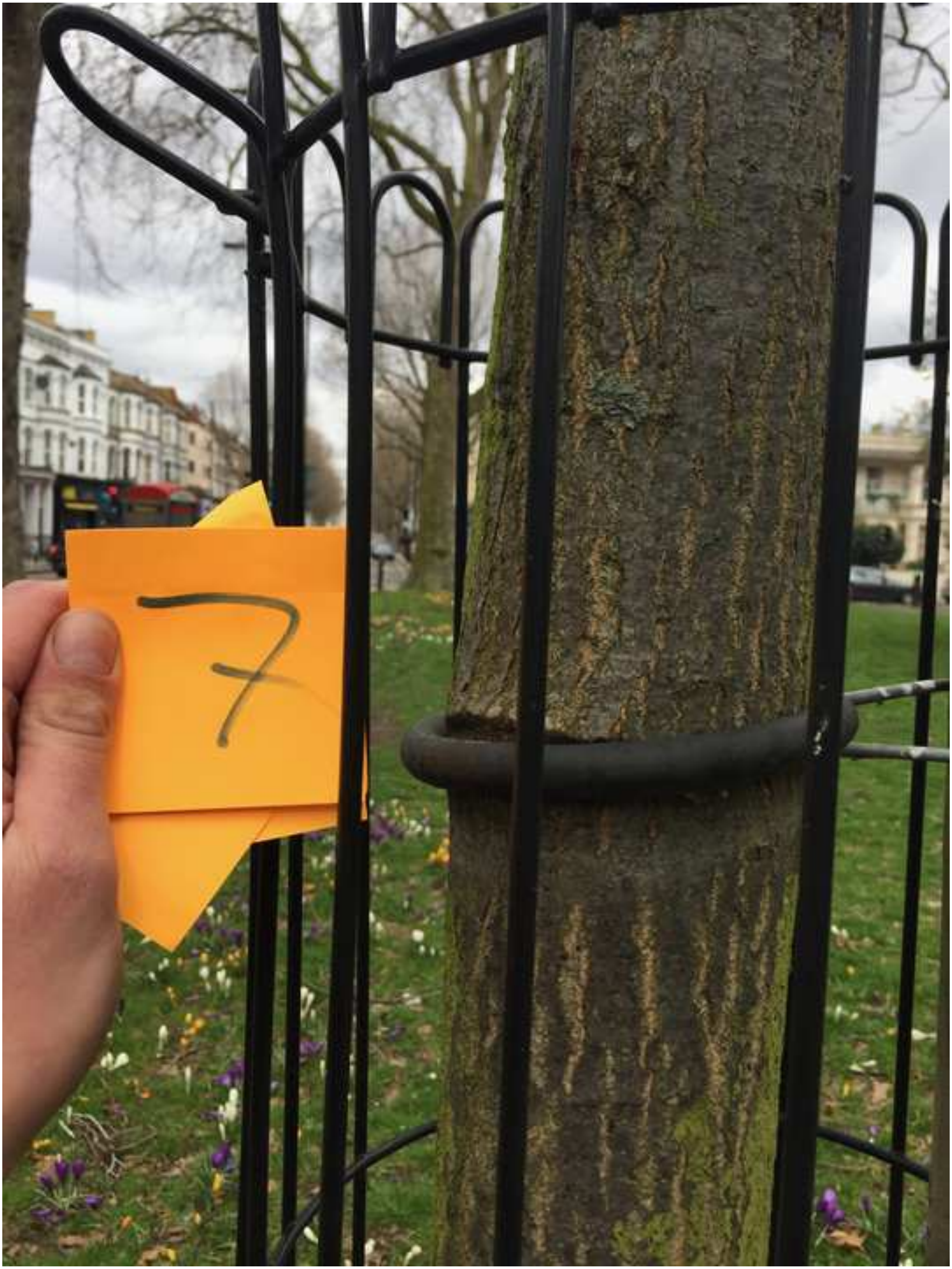
Table

	Angled Post & Tie	Double Post & Crossbar	Double Post & Tie	Integrated Metal Structure & Tie	No Support Structure	Single Post & Tie	Triple Post & Tie	Under ground Guying
Undamaged Specimens	7	17	338	1	16	87	21	10
Specimens with TSPS-associated damage	40 85.1%	22 56.4%	62 15.5%	5 83.3%	43 72.9%	60 40.8%	12 36.4%	21 67.7%
Total	47	39	400	6	59	147	33	31

Table

Abrasion Damage						
Damage	Angled post and Tie	Double post and Crossbar	Double post and Ties	Single post and Tie	Treble post and Tie	Underground Guying
Total	39	16	41	31	11	22
% Damaged	82.98%	41.03%	10.25%	21.09%	33.33%	70.97%
Low (1-2)	0.00%	62.50%	82.93%	38.71%	72.73%	59.09%
High (4-5)	30.77%	12.50%	7.32%	9.68%	0.00%	18.18%
Girdling Damage						
Total	7	10	9	26	6	0
% Damaged	14.89%	25.64%	2.25%	17.69%	18.18%	0.00%
Low (1-2)	71.43%	70.00%	66.67%	61.54%	50.00%	0.00%
High (4-5)	0.00%	0.00%	0.00%	15.38%	33.33%	0.00%
Occlusion Damage						
Total	15	0	0	4	0	0
% Damaged	31.91%	0.00%	0.00%	2.72%	0.00%	0.00%
Low (1-2)	73.33%	0.00%	0.00%	25.00%	0.00%	0.00%
High (4-5)	0.00%	0.00%	0.00%	25.00%	0.00%	0.00%
Adverse Stem Taper (AST)						
Total	5	11	17	33	0	0
% Damaged	10.64%	28.21%	4.25%	22.45%	0.00%	0.00%
Low (1-2)	80.00%	81.82%	88.24%	63.64%	0.00%	0.00%
High (4-5)	0.00%	0.00%	0.00%	27.27%	0.00%	0.00%
Support Rating						
Low (1-2)	17.02%	38.46%	19.50%	21.77%	6.06%	0.00%
High (4-5)	74.47%	23.08%	72.02%	63.95%	81.82%	0.00%
Normal Stem Motion						
Low (1-2)	0.00%	7.69%	1.36%	18.92%	8.00%	0.00%
High (4-5)	72.41%	23.08%	73.02%	52.25%	60.00%	87.10%

Figure



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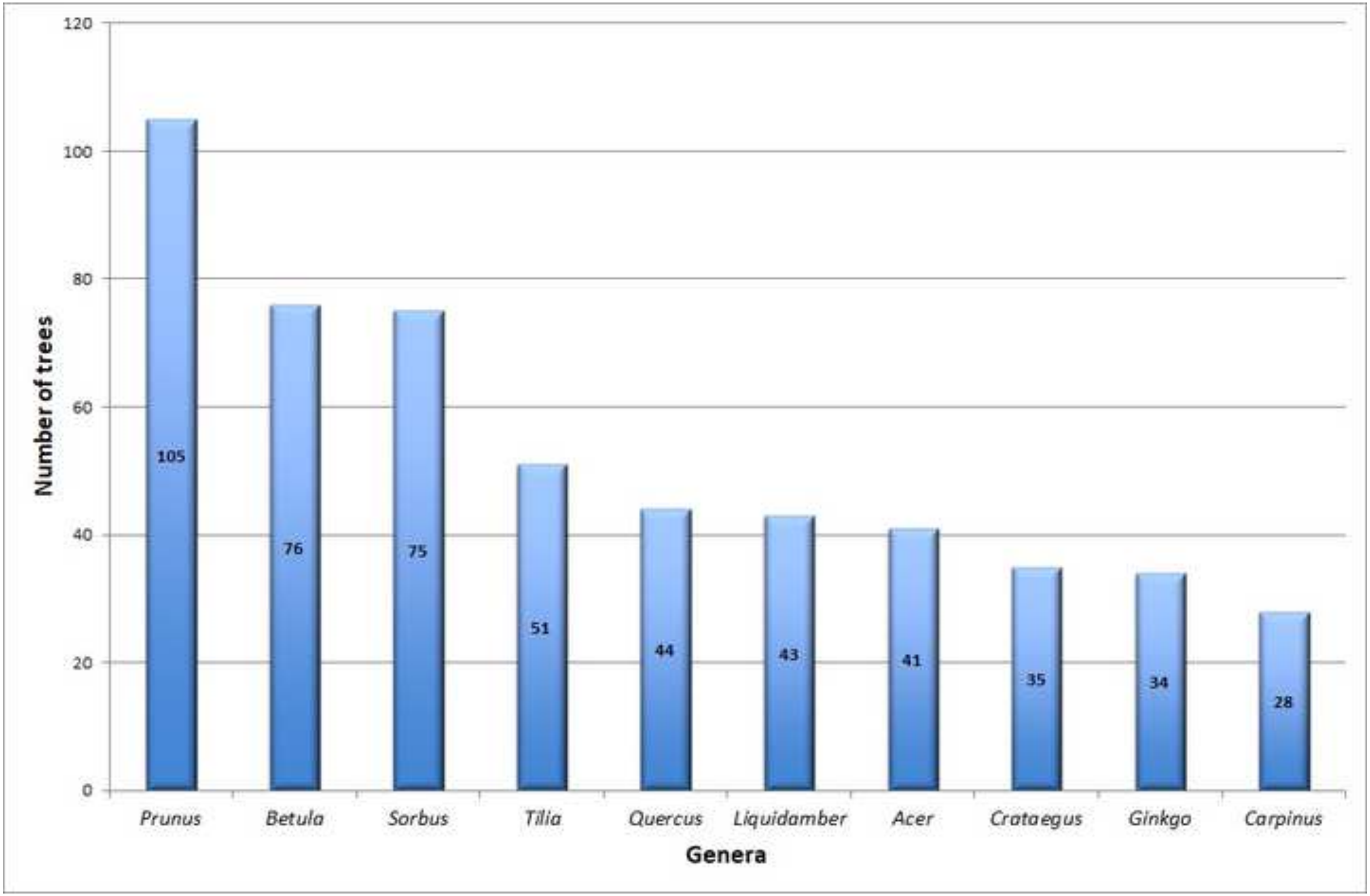
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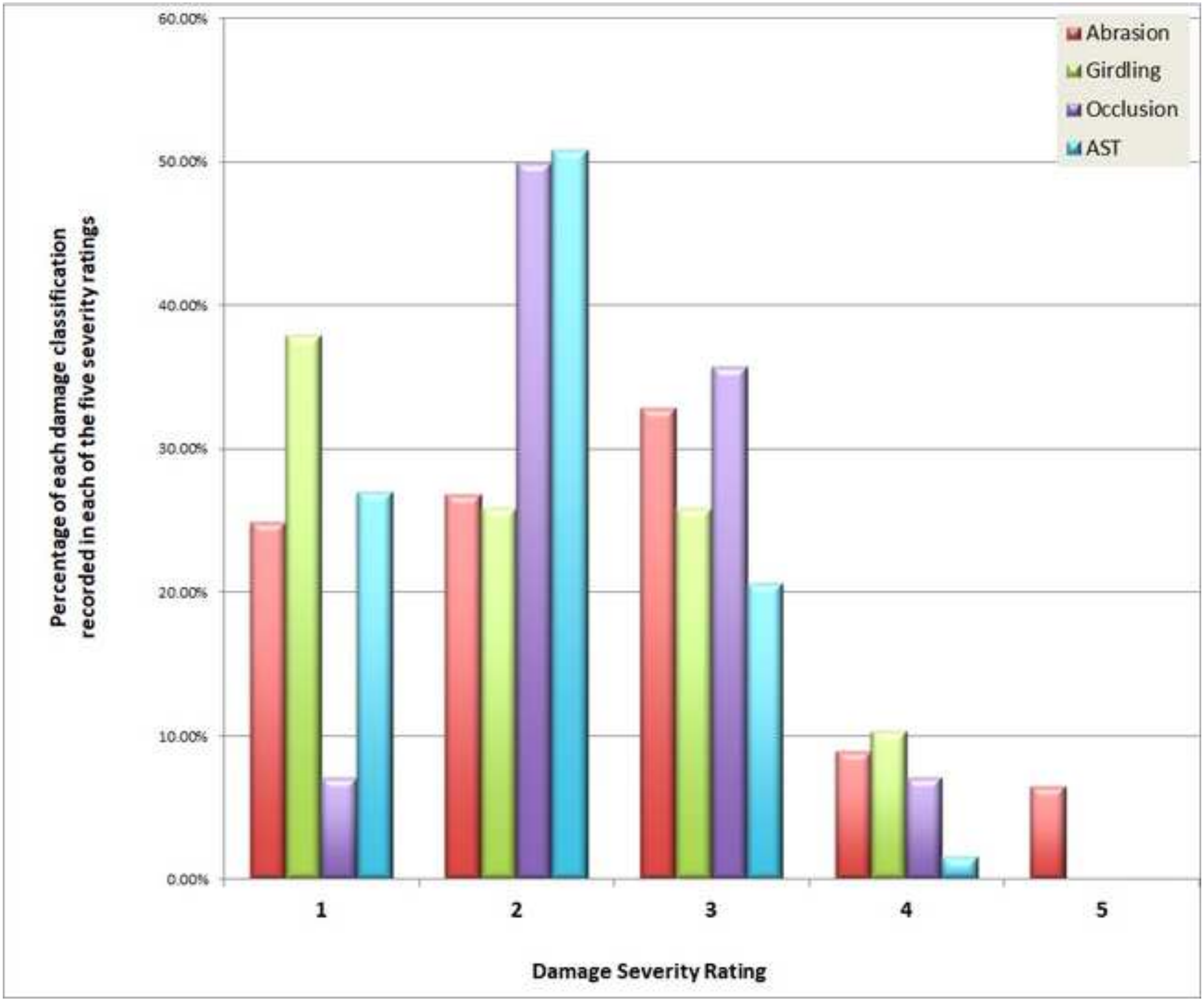
Crataegus
Ginkgo
Carpinus
Genera

Figure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Percentage of each damage classification recorded in each of the five severity ratings
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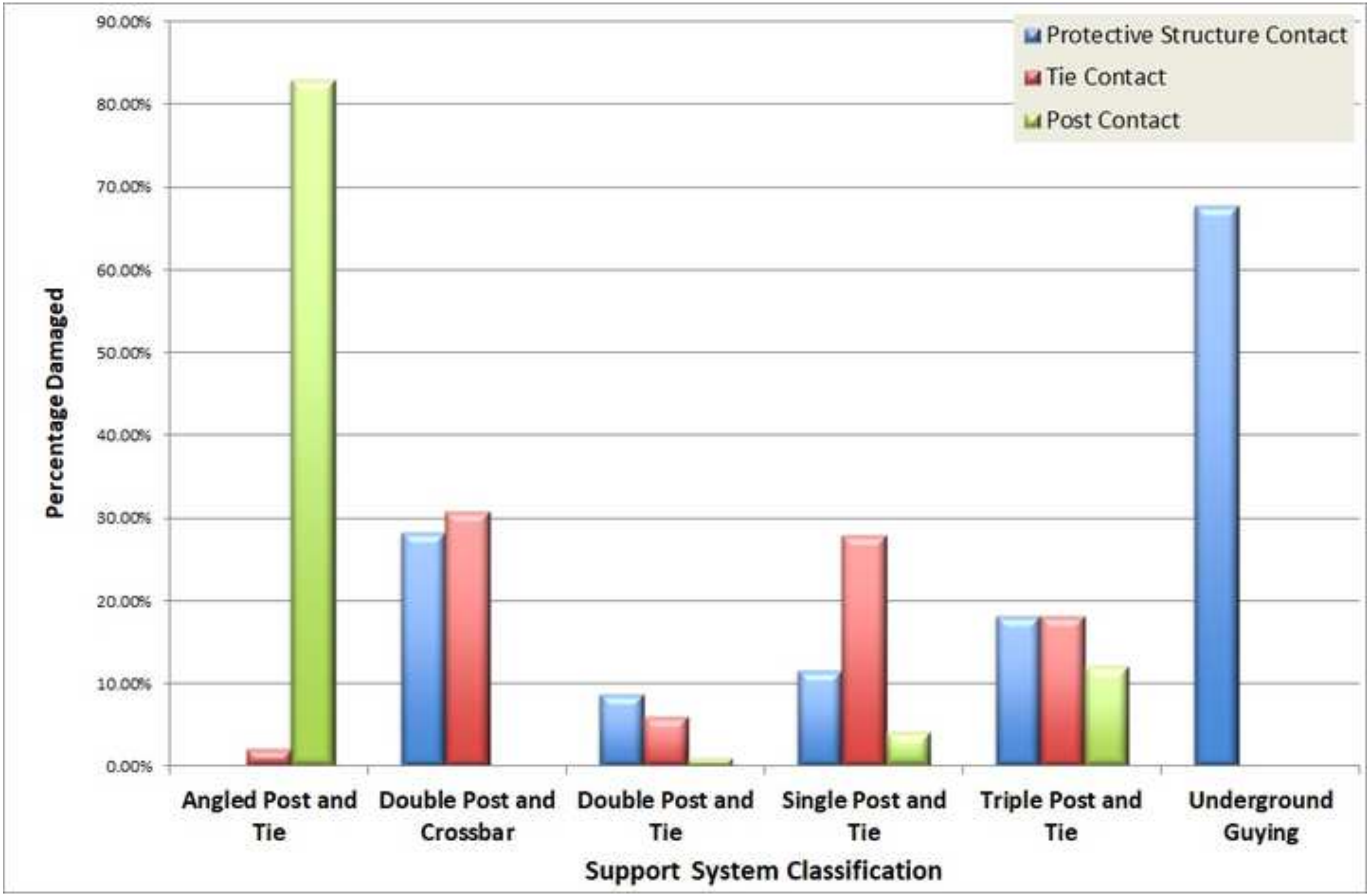
Damage Severity Rating
Abrasion
Girdling
Occlusion
AST

Figure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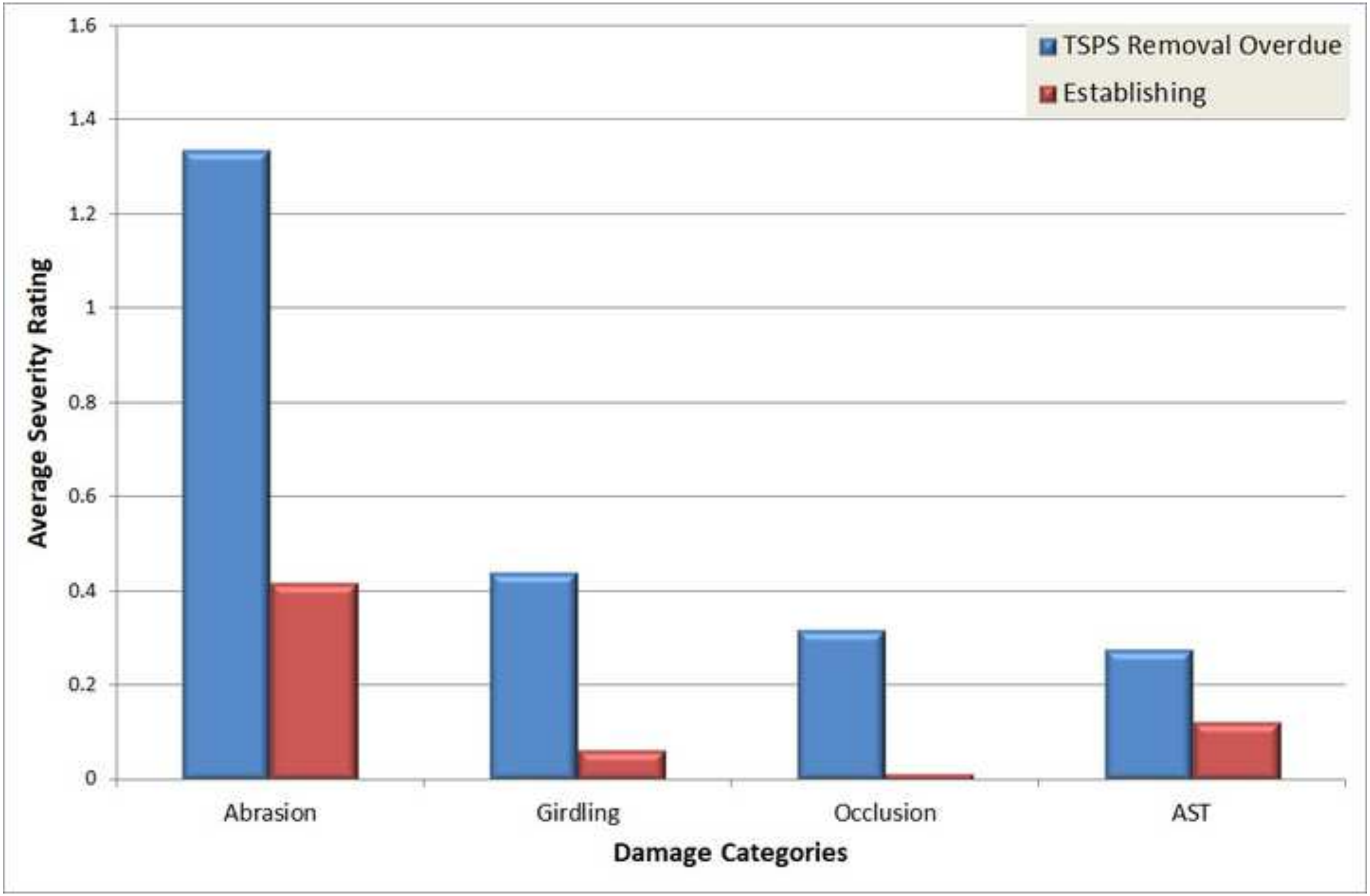
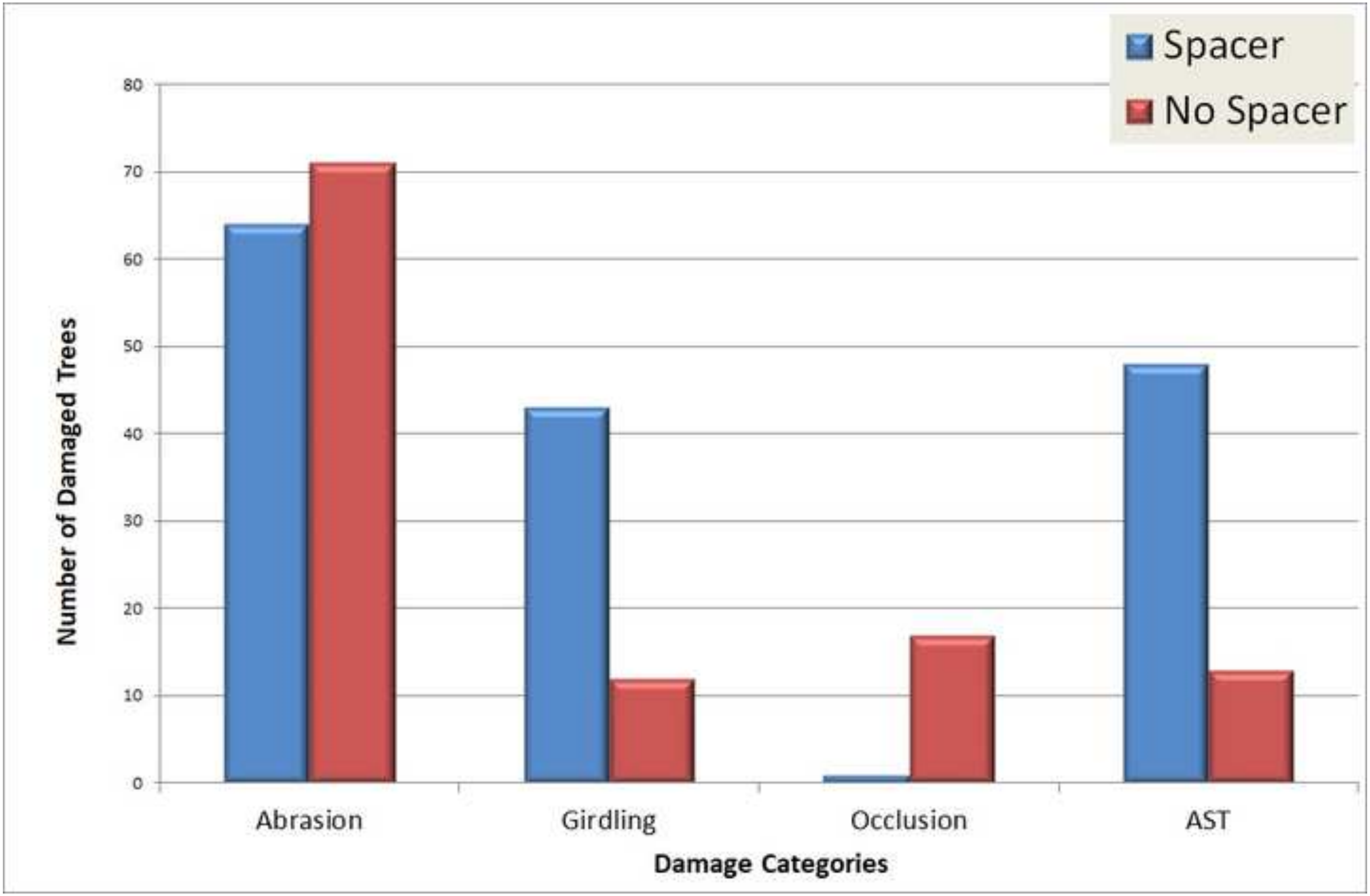
Tie Contact
Post Contact
Angled Post and Tie
Double Post and Crossbar
Double Post and Tie
Single Post and Tie
Triple Post and Tie
Underground Guying
Support System Classification

Figure

Figure


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Average Severity Rating
TSPS Removal Overdue
Establishing
Abrasion
Girdling
Occlusion
AST
Damage Categories

Figure



Spacer
No Spacer
80
70
60
50
40
30
20
10
0
Number of Damaged Trees
Abrasion
Girdling
Occlusion
AST
Damage Categories