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Mahatma Gandhi

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Quantified Tree Risk Assessment: A Critical Review

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1. INTRODUCTION

An important aspect of tree management is to assess the likelihood of a tree causing harm (injury, death and/or property damage, disruption of activities). In recent years, the potential for trees to cause harm has been highlighted by elevated media coverage of tree caused injuries or fatalities. The reality, however, is that the risk of being killed or injured by a tree is extremely low. For example, about three people per year in the United Kingdom (U.K.) are killed by trees in public places, and the fatality risk per tree is 1 in 150 million for all trees in the U.K. or 1 in 10 million for trees in or adjacent to areas of high public use (HSE 2007, NTSG 2011). In the United States (U.S.), there were 407 deaths from wind-related tree failures in the 13 year period 1995-2007 (Schmidlin 2009), or 31 fatalities per year (note that the U.S. population is 5 times that of the U.K.)

There has been much debate about the risk trees pose to human populations. In the U.K., the debate was heightened following a high profile case, *Poll v Bartholomew* (2006) which involved a motorcyclist being hurt by a tree that failed. It was never clarified as to whether the tree fell on to Mr Poll or he came around the corner on his bike and collided with the fallen tree, in any event he sustained personal injuries. In this case, the Court decided that a large private estate did not have an adequate system for the inspection and management of trees, which was an annual drive/walk by assessment. The Court concluded that inspections should be undertaken by qualified and competent inspectors. Speculation that this judgment placed an excessive burden of tree inspections on landowners created an air of anxiety. This resulted in much uncertainty and many trees being unnecessarily felled for fear of litigation (e.g., NTSG 2011). This understandably made decision-makers more risk averse than they otherwise might have been.

Systems have been developed to try and assess the likelihood of trees failing, and the harm that might be caused in the event of failure. Matheny and Clark (1994) developed a hazard evaluation system that assigns a numerical value between 1 and 4 for (i) failure potential, (ii) size of part, and (iii) target rating. These are then totalled to produce a hazard rating between 3 and 12. Other tree risk assessment systems include: THREATS & THREATS-NR (www.flac.uk.com), The

Bartlett Tree Expert Company's 'Tree Risk Management' 2nd Edition (Smiley et al. 2007), and the ISA's Best Management Practice for Tree Risk Assessment (Smiley et al. 2011).

Ellison (2005) took a probabilistic approach to risk, and developed the Quantified Tree Risk Assessment (QTRA) system. This system attempts to provide a quantitative framework for the assessment of the three components of tree risk: (i) target value, (ii) probability of failure, and (iii) impact potential. The system assesses the probabilities of the three components of risk and calculates their product, which allows skilled tree inspectors to quantify the risk of harm from tree failure, which in turn facilitates the balance between tree safety and tree value.

Quantified Risk Assessment (QRA) has been in wide use in risk management since the 1960. The QRA assesses hazard likelihood and system vulnerability using sound physical modelling of failure processes, and recognition of uncertainty and variability of influencing variables. This is absent from the QTRA system which seems to rely more on subjective assessments, particularly for probability of tree failure. Moreover, the QTRA system does not consider 'benefits' in the risk assessment component where costs and benefits are compared, but rather relegates this to information contained in the practice notes.

In principle, QTRA is a welcome development because a quantified risk-based approach to tree management is based on sound decision support principles. This paper explains the principles of QRA, and identifies some weaknesses in the QTRA process that could be rectified by the incorporation of additional QRA principles in any revision of QTRA. The paper will also show how a cost-benefit analysis that considers risk of harm, costs of tree removal, benefits of tree amenity, and other costs and benefits can be used to compare costs and benefits in a rigorous manner. This type of risk and economic assessment can better inform decision-makers.

2. QUANTIFIED TREE RISK ASSESSMENT (QTRA)

The QTRA process is developed and documented by Ellison (2005) and the Quantified Tree Risk Assessment User Manual V3.06 (2012). Risk of harm (ROH) is calculated as (Ellison 2005):

Risk of Harm = Probability of failure × Target value × Impact potential (1)

where 'harm' is defined as serious injury or death. Probability of failure is the annual probability that a tree or selected tree-part will fail. The target value is the probability that a person, vehicle or property will be impacted. The impact potential is the probability of harm a falling tree, or part of a tree, can cause to a pedestrian or vehicle. The risk is deemed "unacceptable" if the ROH exceeds 1 in 10,000.

3. CASE STUDY - LAMAN STREET FIG TREES IN NEWCASTLE

The city of Newcastle in New South Wales (Australia) had 17 mature fig trees (*Ficus microcarpa* var. *hillii* (Hill's weeping fig) on both sides of Laman Street in the heart of the city, see Figure 1. These trees were estimated to be in excess of 70 years of age. They have been lopped (topped) on multiple occasions. Over the last few decades, however, lopping treatment has ceased and trees were left unpruned. Although growing in confined openings between the street and footpath (sidewalk), the trees were considered to have good health and vitality. Some of the trees had started to grow partially over the adjacent hard surfaces.

In June 2007, a severe east-coast low caused wind speeds of 124 km/hr and intense rainfall. As a result, gaps appeared between the base of four trees and the adjacent hard surfaces, see Figure 2. Without any further testing, three of these trees were removed. The fourth tree that was thought to have moved was monitored over the following month to check for further movement. This tree was then determined by Newcastle City Council (NCC) to be stable, and subsequently retained. It is important to be aware that, even if the trees had moved, this movement would not have harmed people or property as this was a serviceability failure rather than a structural failure.

In August 2009 NCC engaged a consultant to assess the stability and safety of the remaining 14 trees. The Stage 1 Visual Tree Assessment concluded that "*the trees with the shortest SULE (Safe Useful Life Expectancy) will dictate the outcome for the entire group. The shortest SULE is category 4: remove within 5 years*" (Marsden 2009). In response to this determination NCC sought to have the risk posed by the trees assessed in order to determine an appropriate management strategy.

In September 2009, a Quantified Tree Risk Assessment (QTRA) was prepared for Newcastle City Council. It concluded that the risk of harm (ROH) was 1 in 19.8 per tree per year, and that the probability of tree failure was 1 in 7.5 per tree per year (see Table 1). A subsequent report by another arboricultural consultant reviewed this first QTRA report and concluded in 2010 that *"On review I believe that this report provides a reasonable assessment of the quantified risk of harm."*[1] Both consultants were 'licensed' QTRA practitioners. Since the ROH exceeded the QTRA suggested ROH threshold of 1 in 10,000,

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[1] key documents are available on the NCC web site: www.newcastle.nsw.gov.au/environment/tree_management/laman_street_figs/key_documents

the reports declared the level of risk as "unacceptable". Based on the level of risk, NCC made a decision to remove the trees in late 2011, and the trees were finally removed in February 2012.

The 14 remaining trees survived for over 4.5 years (June 2007 to February 2012) before they were eventually removed. While there may be some correlation between tree performance along a street, there is no evidence of this occurring in Laman Street as failures were isolated events (i.e. one or two trees may fail, but not all trees at the same time) due to the high variable nature of localised tree root conditions and wind environment. In the absence of evidence to the contrary, these trees can be treated as statistically independent. Using the QTRA results the expected (average) number of deaths or serious injuries in four and a half years between the storm and tree removal is

$$E(\text{fatalities}) = N \times ROH \times \text{time} = 14 \times 1/19.8 \times 4.5 = 3.2 \text{ fatalities or serious injuries}$$ (2)

where N is the number of trees (N=14), and T is the time period in years (T=4.5)

Similarly, the expected (average) number of failures in four and a half years is

$$E(\text{tree failures}) = N \times Pr(\text{tree failure}) \times \text{time} = 14 \times 1/7.5 \times 4.5 = 8.4 \text{ tree failures}$$ (3)

The probability that no tree should fail in four and a half years is

$$Pr(\text{no tree failures}) = [1 - Pr(\text{tree failure})]^{N \times \text{time}} = [1 - 1/7.5]^{14 \times 4.5} = 0.012\% \text{ or } 1/8,000$$ (4)

and so the probability of at least one tree will fail in four and a half years is

$$Pr(\text{at least one tree failure}) = 1 - [1 - Pr(\text{tree failure})]^{N \times \text{time}} = 1 - [1 - 1/7.5]^{14 \times 4.5} = 99.99\%$$ (5)

These relatively straightforward probabilistic analyses were not included in the consultant reports prepared for NCC. Likewise, these probabilities appear not to have been considered and/or appropriately weighed by NCC in making the decision to remove the trees. This type of analysis enables a 'reality check' when extrapolating rates of failure and harm for a single tree to a group of trees. These analyses indicate that the ROH provided to NCC by the QTRA assessors were excessively high. Moreover, all 14 trees remained upright, despite a predicted 99.99% probability that at least one tree would fail in a 4.5 year period.

A risk of death (or harm) per tree per year of 1 in 19.8 is the highest estimate observed by the lead author for any activity. A single fig tree in Laman Street is ten times more dangerous than smoking 10 cigarettes a day (BMA 1990), ten times more dangerous than World War Two (Mueller and Stewart 2011), 75 times more dangerous than mountain climbing (BMA 1990), and 500,000 times more dangerous than trees in public places in the U.K. (see Introduction where fatality risk per tree is 1 in 10 million for trees in areas of high public use).

A QTRA of the 14 trees was undertaken by Mike Ellison in January 2012. He estimated the ROH to be 1 in 170,000 for the worst tree, and ROH of 1 in 2,000,000 for the best tree (see Table 1). The largest discrepancy occurred in the estimation of probability of failure. The fact that two 'licensed'

QTRA practitioners can calculate a ROH that is more than 8,000 times higher than that derived by the developer of QTRA is a cause for concern.

4. QUANTIFIED RISK ASSESSMENT (QRA) AND DECISION-MAKING

There is a long history dating from the 1960's on QRA and its application to decision-making. Applications of QRA range from assessing the safety of nuclear power plants, off-shore platforms, aircraft, missiles, toxic materials to assessing the cost-effectiveness of medicines to road safety to aviation security to flood protection for communities. These applications arise because there is uncertainty and variability of the hazard and risks, the costs of failure are high or catastrophic, costs of protection are also high, and public safety needs to be safeguarded. The decisions also affect many interested parties, so there is a need for a decision process that has scientific rigour, is transparent, and acceptable to society. An understanding of the principles and practices that underpin QRA provide context for future developments to QTRA. We would recommend that the QTRA system should develop longer and more intensive training that includes the principles of QRA as a starting point.

4.1 Risk Assessment Process

In performing a QRA, a number of steps are basic to the analysis, and independent of the system being considered. As applied in the engineering, insurance, pharmaceutical, and many other industries for many decades, the basic definition of risk has been standardized by international agreement (ISO 31000-2009). The process is shown in Figure 3 and can be summarised as (Stewart and Melchers 1997):

1. **Define context.** The system being examined, and the internal and external influences, must be known and defined.

2. **Analyse hazard scenarios.** Identification of what might go wrong, when and where, is crucial to the analysis. Once the potential threats and scenarios have been identified, it is necessary to identify how and why these threats or scenarios can be realised.

   It requires the threat or hazard scenarios to be examined (and understood) in considerable detail. Information from databases and other past experiences will play an important part in hazard scenario analysis.

3. **Analyse risk**

   RISK = (probability of failure) × (consequences) (6)

   Risk (or expected loss) may be given in terms of dollars, the number of human fatalities, etc. for a specific time period (often annually). Typically, the probabilities are estimated from a combination of relevant data and statistics, predictive models of system reliability, and subjective judgments as a last resort.

4. **Evaluate risks.** Analysed risk must be compared with criteria of risk acceptability, usually applying past experience as a guide. If the risk of death is less than one

in a million per year, risks are conventionally considered acceptable if the benefit exceeds the cost.

5. **Treat the risk.** If the estimated risk exceeds the risk acceptance criteria, risk treatment is required. This may involve risk avoidance, risk reduction, or risk transfer. In all cases, the proposed course of action requires careful evaluation. Consideration must be given to possible options and to the likely effect of their implementation, such as opportunity costs. This might involve one or more new risk analyses to gauge the effect of changes.

6. **Monitor and review.** Usually a risk analysis presents only a snapshot of the risk at a particular point in time. Therefore, there is a need to monitor the system and to repeat the risk analysis at regular intervals.

The key objective of a risk assessment is to make an informed risk-based decision. Thus, evaluating the risk by deciding on risk acceptance criteria is a crucial step. In the steps above, the two substantive and challenging steps are (i) analysing the risk, and (ii) evaluating the risk. These two steps are now discussed.

4.2 Analyse Risk

Assessing the consequences of system failure is often relatively straightforward. The consequences of a failure event are generally measured in terms that directly affect people and their environment such as loss of life or injury and economic losses. The estimation of consequences can often be fairly accurate. For example, the consequences of a bridge collapse are cost of replacing the bridge, vehicle occupant fatalities, and indirect losses due to traffic diversions, loss of business/productivity and other social costs. The most contentious issue is how to place a monetary value on a human life. Paté-Cornell (1994) suggests that a cost per life saved of $2 million or less is appropriate for current practice, and the United States Department of Transport adopts a figure of $3 million (Viscusi 2000). For homeland security cost-benefit assessments, Robinson et al. (2010) recommend a Value of Statistical Life (VSL) of $6.5 million in 2010 U.S. dollars. For most activities a VSL ranging between $2-$10 million is typical (Viscusi 2000), as this provides a reasonably accurate reflection of societal considerations of risk acceptability and willingness to pay to save a life.

Estimating the probability of failure is, in general, more challenging to predict than consequences. This is particularly so for low probability events, where failures are rare and the system under consideration is unique or one-off in terms of its design, manufacture, operation or environment (such as offshore platforms, long-span bridges). For engineering systems, failure probabilities are often calculated from computational models that consider the variability and uncertainty of system response, loads, environment, and workmanship. Such analyses can take many person-years to develop. If performance data are available in terms of failures and successes then statistical methods can be used to calculate failure probability and databases assemble such statistics. Either way, a thorough understanding of statistics and probabilistic methods is required.

As a last resort, expert opinions may be elicited (Ayyub 2001, Paté-Cornell 2002). Expert opinions are subject to a number of issues and problems and so should be used with some caution. However, Paté-Cornell (1986) concludes that '*experts' opinions are indispensable given the scarcity of unquestionable data sets*'.

What underpins any method for estimating failure probabilities is an understanding of the failure modes and their cause. In other words, sound physical modelling of failure processes, and recognition of uncertainty and variability of influencing variables, will lead to more robust estimates of failure probabilities.

4.3 Evaluate Risks or Risk Acceptance Criteria

While risks are seldom acceptable, they are often tolerable (or accepted reluctantly) if the benefits are seen to outweigh the costs. The Health and Safety Executive in the United Kingdom puts it this way:

> *"Tolerability does not mean acceptance. It refers to the willingness to live with a risk to secure certain benefits and in the confidence that it (risk) is being properly controlled. To tolerate a risk means that we do not regard it as negligible or something we might ignore, but rather as something we need to keep under review and reduce still further if and as we can."* (HSE 1992).

There is a large amount of literature devoted to the problem of how to define what risks are acceptable to society, and those which are not, since all activities bear some risk (for a review see Stewart and Melchers 1997). The regulators of potentially hazardous industries and activities such as the U.S. Nuclear Regulatory Commission, Federal Aviation Administration, and the Environmental Protection Agency set risk acceptance criteria based on (i) annual fatality risk, and (ii) cost-benefit analysis.

4.3.1 Annual Fatality Risks

Stewart and Melchers (1997) and Mueller and Stewart (2011) reviewed the quantitative safety goals used by the U.S. Nuclear Regulatory Commission, U.K. Health and Safety Executive, Australian and Dutch hazardous industrial development regulators, and others. The consensus risk acceptance criteria obtained for involuntary fatality risk to an individual are shown in Figure 4, and are designed to provide a viable, if somewhat rough, guideline for public policy:

- Annual fatality risks higher than the range 1×10^{-4} to 1×10^{-3} (one in a thousand to one in ten thousand) are deemed unacceptably high or a *de manifestis* risk.

- Annual fatality risks in the range of 1×10^{-3} to 1×10^{-6} (one in ten thousand to one in a million) are generally acceptable if the benefits outweigh the risks to provide an economic or social justification of the risk.

- Annual fatality risks smaller than 1×10^{-6} to 1×10^{-7} (one in a million to one in ten million) are deemed as negligible and further regulation is not warranted.

4.3.2 Net Benefit or Cost-Benefit Analysis

Many risks can be reduced, but at increasing cost until they become excessive compared with the benefit. If annual fatality risks are not unacceptably high or are negligible, then risks may be acceptable if the benefits outweigh the risks. The 'benefit' is the reduction in risk (damages or fatalities averted) associated with a decision, and the 'cost' is the cost of the decision. The net benefit or net present value (NPV) is equal to benefit minus the cost. The net present value or net benefit is (e.g., Stewart 2010):

$$NPV = E(B) + \Delta R \left[\Pr(failure) \times Consequences \right] - C_{\Delta R}$$

(7)

where E(B) is the expected benefit from the decision not directly related to mitigating the risk; Pr(failure) is the probability of failure assuming no risk mitigating measures; and Consequences is the loss or consequence if failure occurs. The reduction in risk (ΔR) is the degree to which the decision or risk mitigating measures reduces the likelihood of failure and/or the losses sustained in a failure. The cost of reducing the risk including opportunity costs is $C_{\Delta R}$. This equation can be generalised for any time period, discounting of future costs, and more detailed time-dependent cost and damage consequences. If NPV>0 then there is a net benefit and so the measure is cost-effective.

4.3.3 Risk Aversion

For low probability-high consequence events decision-makers tend to be risk-averse because of the catastrophic or dire nature of the hazard or event. However, while many individuals may be risk-averse, government and society are risk-neutral when assessing risks because governments have a high degree of cost and benefit diversification not available to individuals (Sunstein 2002, Faber and Stewart 2003, Ellingwood 2006). A 'risk neutral' risk assessment entails using mean or average estimates for risk and cost-benefit calculations, and not worst-case or pessimistic estimates, as mandated, for example, by the U.S. Office of Management and Budget (OMB 1992).

Probability neglect is a form of risk aversion as decision-makers are clearly averse to events of large magnitude irrespective of the probability of it actually occurring. Utility theory can be used if the decision maker wishes to explicitly factor risk aversion into the decision process (Jordaan 2005, Stewart et al. 2011).

The issue of risk aversion is not a new one, but has been well researched and documented for politically sensitive and controversial decisions such as nuclear power safety and aviation safety. In these cases, risk acceptance criteria have been developed based on annual fatality risks and net benefit analysis using expected (mean) values.

4.3.4 Peer Review

Finally, a peer review will add to the quality of the risk analysis and assessment, and the decision-making process and so enhance the credibility of decisions. This is particularly so for decisions which have the potential for political and public repercussions or where the assets have heritage, ecological or

cultural significance.

5. QUANTIFIED TREE RISK ASSESSMENT (QTRA)

5.1 Calculation of Risk of Harm

The probability of failure is the most subjective parameter to quantify when estimating Risk of Harm. According to the QTRA User Manual V3.06 (2012) there is an order or more of magnitude between each probability of failure range used on the QTRA calculator starting from 1/1 and ranging to 1/1,000,000. The QTRA User Manual (2007) points out that trees that have a low probability of failure *"are at significant risk of failure only during very extreme weather events"*, a statement supported by the observations of Guggenmoos (2010) in relation to damage to overhead power lines following catastrophic storm events in North America.

There seems to be little guidance to QTRA practitioners on how to assess the probability of failure. There are no instructions on how to undertake a statistical analysis of tree failures, how likelihoods may be estimated from wind speed and rainfall records (if these are the hazards contributing to failure), how mode of failure affects failure probabilities, how to estimate 90th or 95th percentile confidence intervals on predictions, or how to extrapolate probability of failure per tree to a group of trees, see Equations (2) to (5). At this moment, the QTRA process of estimating probability of failure is subject to a degree of uncertainty because of the complex variables involved in tree biomechanics and tree failure, variable weather conditions, and varying levels of expertise of the assessors.

There is also a need to compile datasets on tree failures and failure rates in a format suitable for benchmarking. The International Tree Failure Database (ITFD), for example, may be very useful for determining the number of failed trees, but a calculation of probability of failure (failure rate) requires also the number of trees that have not failed (ie. unfailed trees), and the time period over which failures were observed, see Eqn. (10).

Benchmarking allows the predicted probability of failure to be compared to known statistics of failure obtained from relevant datasets. For example, is the assessed tree likely to be 10 times more likely to fail than an average tree, about the same, or 10 times less? Probability of failure may also increase with time if deterioration is observed, or perhaps those that have failed were weaker and so remaining trees are less vulnerable. Calculated risks will be most sensitive to probability of failure, and more scientific approaches and detailed guidelines are needed to better estimate this parameter.

The QTRA guidelines provide significantly more detailed instructions on quantifying target value. This is to be expected since it is not particularly difficult to assess the likelihood that people or vehicles will be under a tree at any point in time. In a busy street it will be approximately 50-100%, and for a park, maybe 10-20%. Either way, any estimate will be accurate to ±10-20%.

One issue that needs further elaboration is that trees are most vulnerable during periods of high wind and/or rain. These are circumstances where many people avoid the outdoors thus reducing the target value quite considerably. Although the influence of weather is not discussed by Ellison (2005), it is discussed and some guidance is provided in the QTRA User Manual (2012).

The guidelines for impact potential are quite prescriptive, and are based on size of tree part likely to impact the target. Impact potentials vary from 1/1 (100%) for a 450 mm diameter tree part to 1/2,500 for a 10-25 mm tree part. If a tree or tree-part were to fall, and a person was under the tree at the time, there will not be 100% surety of harm to the person no matter how large the tree-part. A tree has a large canopy, and a tree could fall away from an individual, or a tree-part fall on the opposite side to where a person is standing. Therefore, the upper limit of 100% seems too high, and a more reasonable upper limit may be say 25% or 50% depending on the size of the tree. Impact potentials would seem to be over-estimated in the QTRA guidelines.

Finally, there is some evidence that results from a QTRA are highly subjective. Norris (2007) asked twelve experienced arborists to assess eight trees using eight different risk assessment methods (see Figure 5). For QTRA, the risk of harm ranged from 1/19 to 1/128 million. The lowest and highest values were obtained from QTRA licensed practitioners. The range in probability of failure was 1/2 to 1/50,000. Such a large discrepancy should be a concern, as should the discrepancies between two licensed QTRA practitioners and Mike Ellison who developed QTRA, in the case of the Laman Street fig trees.

5.2 Risk Acceptance Criteria

If the ROH exceeds 1 in 10,000 then the QTRA process deems that the risk is "unacceptable" and remedial action is needed to reduce the risk to an acceptable level (Ellison 2005). In principle, this risk acceptance criterion has much merit, but may be viewed as prescriptive. There is much evidence that annual fatality risks that exceed 1 in 1,000 are unacceptable, and that risks between 1 in 1,000 and 1 in 1 million may be acceptable if the benefits outweigh the risks (see Section 4.3.1). There is no clear consensus about at precisely what level risks become unacceptable, so any prescribed safety goal needs to be interpreted with some flexibility. Ellison (2005) notes that "*the hazard could confer benefits that might be set against the risk of harm*". This infers a cost-benefit assessment, but the QTRA process does not offer guidance on how a cost-benefit analysis should be undertaken. The two cost-benefit examples to follow are provided to illustrate some key cost-benefit assessment concepts.

5.2.1 Example 1 - Net Benefit of Tree Removal

Let us assume that tree removal is the recommended decision, and this will cost $10,000 per tree. If this cost is spread over T years, then the annual cost discounted to present values is

$$C_A = \frac{C_T}{\displaystyle\sum_{t=1}^{T}\frac{1}{(1+r)^t}}$$

(8)

where C_T is the total cost and r is the discount rate. If costs are annualised over T=10 years at r=3% then this gives a present value of approximately $1,200 per year. This might be viewed as a direct cost. However, an opportunity cost might also be associated with loss of amenity (shade, viewpoints, property value) which might be say $1,000 or $5,000 per year.

The benefit of tree removal is that it will remove all risk, and so ΔR=100%. Another benefit of tree removal is that it may eliminate root damage to pavement and services producing maintenance savings of $250 per year. The losses if a tree were to fail would be damage to adjacent property and loss of life totalling $5 million.

All costs are converted to annual costs to ensure consistency of units. All values are illustrative only to help explain parameters and trade-offs between costs and benefits. The NPV or net benefit for tree removal is (Eqn. 7):

$$\text{NPV} = E(B) + \Delta R \left[\text{ROH} \times C_{loss} \right] - C_{\Delta R} \quad (9)$$

where

- ROH = annual risk of harm (ROH) per tree

- E(B) = $250 per year (no root damage to infrastructure)

- ΔR = 100% (tree removal eliminates all risk)

- C_{loss} = $5 million (consequences of tree failure)

- $C_{\Delta R}$ = $1,200 per year (cost of tree removal and no loss of amenity)

- $C_{\Delta R}$ = $2,200 per year (cost of tree removal and $1,000 loss of amenity)

- $C_{\Delta R}$ = $6,200 per year (cost of tree removal and $5,000 loss of amenity)

Table 2 shows that net benefit varies as a function of ROH for losses of amenity of $0, $1,000 and $5,000 per year. If ROH is 1/100 then net benefit of tree removal is $44,000-$49,000 with net benefit highest when there is no loss of amenity. When ROH=1/1,000 then the net benefit of tree removal reduces to $4,050 and $3,050 for loss of amenity of $0 and $1,000, respectively. However, when ROH=1/1,000 and loss of amenity is $5,000 per year then there is not a net benefit of tree removal, but a net loss of $950 per year. A lower ROH of 1/10,000 produces net losses irrespective of level of loss of amenity. To be sure, more detailed analyses are possible, but this example shows that even if ROH exceeds the prescribed QTRA safety goal of 1/10,000, there can still be a net benefit to retaining a tree once all costs and benefits of tree removal are considered.

5.2.2 Example 2 - Net Benefit of Risk Mitigating Measure

Rather than removing the tree it is possible to employ a risk mitigation strategy to reduce the exposure of people to a potential hazard. This might include, for example, restricting vehicle access to an adjacent road, redirecting pedestrian traffic, or closing the street on high wind days. Such risk mitigation measures might be expected to reduce the target value considerably. We assume a 75% reduction in target probability, equivalent to a risk reduction of ΔR=75%. The cost of risk mitigation measures may be $15,000 per year.

Maintenance costs associated with root damage to pavement and services costs $250 per year. Hence, $C_{\Delta R}$ =$15,250 per year, and C_{loss}=$5 million as assumed above. A benefit of retaining the trees may be public amenity, which may vary from E(B)=$1,000 to E(B)=$5,000 per year.

Net Benefit is calculated from Eqn. (9) using the parameters described above (see Table 3). If the ROH is 1/100 or greater then risk mitigating measures are cost effective. However, the benefits of such measures reduces as ROH decreases, even when the public amenity and benefit of retaining the tree is valued at E(B)=$5,000 per year. If the ROH is 1/100, the net benefit for tree removal is $49,050 (assuming no loss of amenity), and $22,500 if risk mitigating measures are put in place that reduce risk by 75% (compare Tables 2 and 3). It follows that a decision aimed at only maximising net benefit would be to remove the tree - this assumes that economic assessment is the sole criterion for decision making. However, if a decision was to retain the trees for non-quantifiable reasons (heritage value, tourism, etc.) then risk mitigating measures are also cost-effective and justifiable with a net benefit of at least $22,250. Clearly, different cost inputs will lead to different results and decisions.

5.3 Improvements to QTRA

The priority for improvement lies in more accurate and robust assessment of failure probabilities, as this is the parameter in the risk equation subject to the highest uncertainty (and error). The element of subjectivity needs to be ameliorated. This means more scientific approaches are needed, and that results are benchmarked with known risks to ensure that results pass a 'reality check'. The figures used by the assessor must have at least some semblance to reality.

Hazard identification is an important first step to understand the cause of tree failure, and then the frequency and severity of these events. This might involve assessing the annual probability that a wind speed exceeds a certain value, or rainfall exceeds a specific value. Statistical and probabilistic models for natural hazards are well researched and documented; for example, Wang and Wang (2009) provide stochastic wind field models for most locations in Australia for cyclones and storms.

If the tree under consideration is similar in age, condition and exposure to other trees, then the failure probability may be derived as

$$\text{Probability of Failure} = \frac{n(\text{failed trees over time period T})}{N \times T} \text{ per year} \quad (10)$$

where n() is the number of failed trees over time period T, N is the total number of failed and unfailed trees, and T is measured in years. It is preferable to consider times periods in excess of one year as this will average out the failure probability over time and be more likely to consider the effect of extreme events.

The larger the sample size (NxT) the more confidence there is in the calculation. It follows from binomial theory that the 90% confidence limits of such as a result is

$$\text{Probability of Failure} \pm 1.645 \sqrt{\frac{\text{Probability of Failure} \times (1 - \text{Probability of Failure})}{N \times T}}$$

(11)

Taking the Laman Street figs as an example, if n(failed trees) is 2 over T=10 years, and total number of trees is N=16, then the probability of failure given by Equation. (10) is 0.0125 or 1/80. The 90% confidence interval for this estimate is 0.0125±0.0144 which means that there is 90% probability that the probability of failure lies between 0.0 and 0.0269 (1/37). Calculations such as these help provide an indication of upper and lower bounds.

If statistically robust estimates of probability of failure are not available, then the probability of failure of the tree under consideration may be compared with an average tree where the probability of failure is known. For example, the probability of failure of trees in public places in the U.K. is at least 1 in 10 million (assuming target value and impact potential are unity) (HSE 2007, NTSG 2011). An assessment may then conclude that the tree has a risk that is 10 or 100 times higher than a typical tree, or perhaps less. This requires some subjectivity, but helps provide comparative risks.

The setting of risk acceptance in the QTRA process should be broadened to include cost-benefit or other decision theory considerations. Such considerations are particularly useful where the decision has repercussions well beyond ensuring public safety. Risk mitigating measures such as site access restrictions, and tree removal can be assessed in a rigorous and methodical manner that aims to incorporate the costs and benefits of all interested parties.

A QTRA should use mean estimates for risk calculations as governments mandate risk-neutral risk assessments. While it may seem prudent to select conservative estimates, if the QTRA's three parameters are doubled, then ROH increases eight fold. If excessively conservative values are used at each opportunity then the calculated ROH becomes illogical.

A clear example of the consequence of not using the mean (or using the extreme conservative) occurred when an assessor of the figs in Laman Street determined that the probability of tree failure was 1 in 7.5 per tree per year. This figure was derived on the assumption that since two trees failed in 2007, then the likelihood of tree failure would be the same in the following year disregarding the fact that the weather in 2007 was an extreme event with annual probability of exceedance of approximately 5% (Stewart 2012). It also ignored the fact that for the previous several decades no trees failed.

Decisions partially or fully based on QTRA can significantly affect the wellbeing of the public. Thus, the decision-making process should include within it quality assurance measures and a peer review to add confidence to any decision made. Quality assurance procedures tend to focus on internal reviews. Peer review is an independent and critical review of risk analysis and risk assessment procedures and should obviously be conducted by recognised experts. If a peer review produces risks or recommendations that are in conflict with previous reports, then there should be an opportunity for all parties to see if a consensus can be reached. If not, then the decision-makers can decide if more studies are needed, or can make a decision recognising lack of consensus and the use of alternate decision criterion to reach a decision.

Finally, while quantitative decision support tools, such as QRA and QTRA, hold some appeal to decision-makers, they cannot capture the full and diverse range of societal considerations of risk acceptability. Therefore, a QTRA should be viewed only as an aid to decision support, where decisions about public safety will often require social, economic, cultural, environmental, political and other considerations.

6. CONCLUSIONS

A QTRA should be subject to rigorous and independent review to judge the veracity of the calculated risks. The QTRA system should develop longer and more intensive training that includes the principles of QRA as a starting point. This could reduce the risk of wide discrepancies between individual QTRA users. There is also a need for any risk management process involving trees, not only to assess the risk but to consider the benefits provided by trees - i.e., to conduct a risk-based cost-benefit analysis. Whilst crude data sets relating to tree failures do exist, the International Tree Failure Database (ITFD) for example, considerable work is still required in this area. In the meantime, tree risk assessors should, as far as reasonably possible, rely on benchmarks to ensure that their assessments are not outside of the realms of reality and include at least some form of scientific rigour.

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	Probability of failure	Target value	Impact potential	Risk of Harm (ROH) per tree per year
Newcastle City Council Assessment (2009)	1/7.5	1/2.64	1/1	1/19.8
Mike Ellison Assessment (2012)				
Best Tree	1/100,000	1/20	1/1	1/2,000,000
Worst Tree	1/1,000	1/20	1/8.6	1/170,000

Table 1. Results of QTRA for a Single Tree in Laman Street (Newcastle).

	Cost of Tree Removal Including Opportunity Costs ($C_{\Delta R}$)		
Risk of Harm per Tree per Year (ROH)	$1,200	$2,200	$6,200
1/20	$249,050	$248,050	$244,050
1/100	$49,050	$48,050	$44,050
1/1,000	$4,050	$3,050	-$950
1/10,000	-$450	-$1,450	-$5450
1/100,000	-$900	-$1,900	-$5,900
1/1,000,000	-$945	-$1,945	-$5,945
1/10,000,000	-$950	-$1,950	-$5,950

Note: each entry represents benefit minus cost result for each ROH and cost of tree removal.

Entries that are positive would be considered cost-effective to remove a tree.

Table 2. Net Benefit of Tree Removal as Function of Risk of Harm (ROH) and Cost of Tree Removal Including Opportunity Costs ($C_{\Delta R}$).

	Value of Tree Amenity E(B) per year		
Risk of Harm per Tree per Year (ROH) Without Risk Mitigating Measures	$0	$1,000	$5,000
1/20	$172,250	$173,250	$177,250
1/100	$22,250	$23,250	$27,250
1/1,000	-$11,500	-$10,500	-$6,500
1/10,000	-$14,875	-$13,875	-$9,875
1/100,000	-$15,213	-$14,213	-$10,213
1/1,000,000	-$15,246	-$14,246	-$10,246
1/10,000,000	-$15,250	-$14,250	-$10,250

Note: each entry represents benefit minus cost result for each ROH and value of tree amenity.

Entries that are positive would be considered cost-effective to implement risk mitigating measures.

Table 3. Net Benefit of Risk Mitigation that Reduces Risk by ΔR=75%.

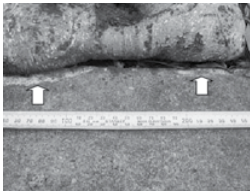Figure 1. Laman Street Looking East – April 2010.

Figure 2. The Gap Observed Between One of the Trees and the Adjacent Hard Surface (Marsden 2007).
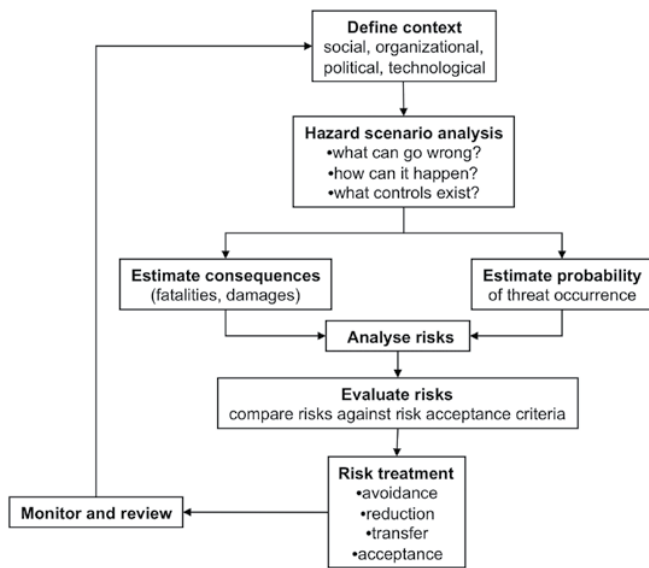

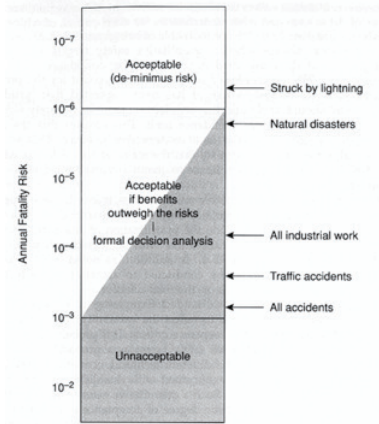Figure 3. Risk Assessment Process.

Figure 4. Generally Agreed Risk Acceptance Criteria for Annual Fatality Risks (Stewart and Melchers 1997).
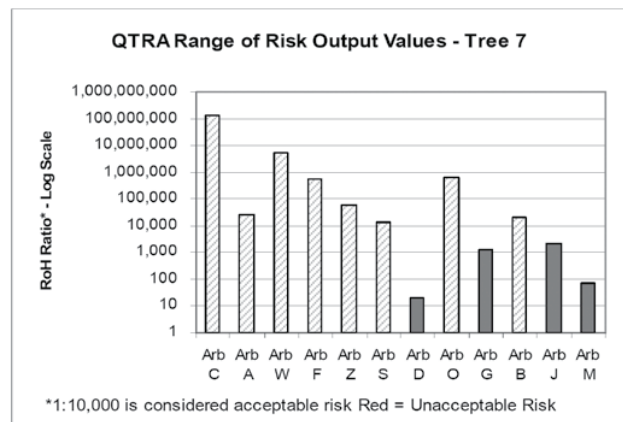

Figure 5. Range of Outcomes Using QTRA (Norris 2007).