果 树 学 报 2018,35(1): 82-93
Journal of Fruit Science

DOI:10.13925/j.cnki.gsxb.20170123

3种热带特色果树寒冻害低温等级指标的确定

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摘 要:【目的】我国莲雾、杧果、青枣寒冻害年年有不同程度的发生。为了达到合理布局,减少寒冻害损失,迫切需要建立3种热带果树寒冻害等级指标。【方法】根据历史气候和大尺度寒冻害灾情考察资料、果园定位观测试验、2 a的地理移放试验、人工气候箱致灾试验等多种试验方法,分析寒冻害调查及试验莲雾、青枣、杧果的形态变化,对照寒冻害形态学标准,确定调查灾情及试验样本灾情等级,采用数理统计和对比印证方法,对热带特色果树寒冻害低温等级指标进行研究。【结果】确定了3种热带特色果树的寒冻害低温等级指标,分别为莲雾:Tmin>5.5 ℃,无寒冻害,正常生长;3.0 ℃<Tmin≤5.5 ℃,轻度;1.0 ℃<Tmin≤3.0 ℃,中度;-1.5 ℃<Tmin≤1.0 ℃,重度;Tmin≤-1.5 ℃,极重,不可恢复或死亡。青枣:Tmin>5.0 ℃,无寒冻害,正常生长;3.0 ℃<Tmin≤5.0 ℃,轻度;0.5 ℃<Tmin≤3.0 ℃,中度;-2.5 ℃<Tmin≤0.5 ℃,重度;Tmin≤-2.5 ℃,极重,不可恢复或死亡。杧果:Tmin>2.0 ℃,无寒冻害,正常生长;0.5 ℃<Tmin≤2.0 ℃,轻度;-1.0 ℃<Tmin≤0.5 ℃,中度;-2.5 ℃<Tmin≤-1.0 ℃,重度;Tmin≤-2.5 ℃,极重,不可恢复或死亡。【结论】莲雾、杧果、青枣等级指标通过人工气候箱致灾试验、地理移放试验和典型年实际灾情验证,验证吻合率高,可以在生产实际中应用。

关键词:莲雾;杧果;青枣;寒冻害;低温指标
中图分类号:S667 文献标志码:A 文章编号:1009-9980(2018)01-0082-12

Determination of cold and freezing injury grade indexes for three tropical characteristic fruit trees

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Abstract:【Objective】The planting benefits of wax apples, mangos and *Zizyphus mauritiana* are relatively large and these fruit trees had developed rapidly in recent years in Fujian, Guangxi, and Guangdong provinces. However, these areas belong to the northern edge of the tropical fruit trees planting area and coupled with the blind actions of farmers, cold and freezing injuries occur annually in varying degrees. Currently, there are no cold and freezing injury grade indexes of *Zizyphus mauritiana* and mangos and only preliminary studies on wax apples. In order to achieve a reasonable layout, to reduce the loss from cold and freezing injuries and to ensure the healthy and stable development of tropical fruit trees, there is an urgent need to establish cold and freezing injury grade indexes for wax apples and mangos and *Zizyphus mauritiana* by using a variety of different methods.【Methods】Based on the historical climate data and the investigated data of large-scale cold and freezing injuries and other experimental methods, the morphological changes of wax apples, *Zizyphus mauritiana* and mangos were analyzed. According to the morphological standard of cold and freezing injuries, the grade of injury samples was determined. On the basis of the cold and freezing grade (x) and the minimum temperature (Td) samples of process before 2015, the relationship between *X* and Td was established by means of mathematical statistics and the grade indexes of

收稿日期:2017-05-05 接受日期:2017-10-23
基金项目:公益性行业(气象)科研专项(GYHY201406027);福建省科技厅农业引导性(重点)项目(2017N0011)
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cold and freezing injuries were preliminarily determined. The grade indexes of three fruit trees were determined by validation methods of artificial climate chamber experiments and geographical transplantation experiments and actual orchard disaster samples in 2016.【Results】The relationship between the grade disaster (*X*) of three fruit trees and the minimum temperature (Td) of the related processes were determined by applying many functional equations, with the results showing that the fitting effect of an equation of one degree, an equation of two degrees and an equation of three degrees was very good. The cold and freezing injury grade (x=0.5, 1.5, 2.5, 3.5) was divided into the following three equations for the fruit trees: the critical thresholds of no to light grade, light to moderate grade, moderate to severe grade and severe to most severe grade at low temperature (Td) could be concluded; the Td values from the three equations were averaged, for the convenience of the application and the values were required to take an integer of 0.5 ℃; our work in this paper determined the cold and freezing injury grades of the three tropical characteristic fruit trees with morphological indexes as follows: wax apple: Tmin>5.5 ℃, without cold and freezing injury, normal growth; 3.0 ℃<Tmin≤5.5 ℃, light injury; 1.0 ℃<Tmin≤3.0 ℃, moderate injury; −1.5 ℃<Tmin≤1.0 ℃, severe injury; Tmin≤−1.5 ℃, most severe injury, no recovery or death. *Zizyphus mauritiana*: Tmin>5.0 ℃, without cold and freezing injury, normal growth; 3.0 ℃<Tmin≤5.0 ℃, light injury; 0.5 ℃<Tmin≤3.0℃, moderate injury; −2.5 ℃<Tmin≤0.5 ℃, severe injury; Tmin≤−2.5 ℃, most severe injury, no recovery or death. Mango: Tmin>2.0 ℃, without cold and freezing injury, normal growth; 0.5℃<Tmin≤2.0 ℃, light injury; −1.0 ℃<Tmin≤0.5 ℃, moderate injury; −2.5 ℃<Tmin≤−1.0 ℃, severe injury; Tmin≤−2.5 ℃, most severe injury, no recovery or death. The grade indexes of our research was verified by the results of the artificial climate chamber experiment: the coincidence rates were 90%, 100% and 100%, respectively, the coincidence rates of the geographical transplantation experiment were 96.3%, 88.2% and 94.1%, respectively and the validation results of a typical year were 91%, 83.3% and 90%, respectively.【Conclusion】The cold and freezing injury grade indexes of the three tropical fruits were determined with the morphological indexes, the grade index was verified by the artificial climate chamber experiment, geographical transplantation experiment and typical year's results, the accuracy rate of validation was high. The grade index could be used in practical applications.

Key words: Wax apple; Mango; *Zizyphus mauritiana*; Cold and freezing injury; Low temperature index

中国是世界热带水果生产大国之一，热带水果产量约占世界热带水果总产量的28%[1]，主要分布在我国南方广东、广西、福建、海南、云南等地。为增强国际竞争力，近十多年来国家出台了一系列政策或文件鼓励热带水果产业发展。青枣、杧果、莲雾等水果由于风味独特、市场需求量巨大、经济效益可观，近年来经过引(扩)种已经成为我国重要特色热带水果，在区域经济中日显重要，发展潜力巨大[2-7]。这些地区属热带果树种植北缘地带，寒冻害年年有不同程度的发生；加之农户不遵循气候规律，在不适宜区盲目引种，加重寒冻害损失，严重制约了热带果树的健康稳定发展。例如，2008年1月的寒害导致华南地区热带果树严重受灾，仅广西百色市右江河谷杧果就有1.8万hm^2受灾，经济损失6 000多万元；据统计，当年海南超过4万hm^2杧果中，有30%受灾，直接经济损失超过2亿元[8]；广西防城港创意农业有限公司莲雾种植基地1 000多株莲雾整株冻死；2005年福州连江县城关种植的6.67 hm^2青枣遭遇冬季冻害，全部死亡，损失惨重。2016年1月24—26日强寒潮造成福建、广东、广西热带果树严重损失。但因热带果树种植效益较高，目前热带果树进一步扩种趋势明显。为了避免再盲目扩种，迫切需要建立热带果树寒冻害等级指标，达到合理布局，减少寒冻害损失。

目前关于香蕉、荔枝、龙眼、枇杷的寒冻害低温等级指标已有大量研究[9-11]，龙眼、枇杷已形成标准[12-13]；未见青枣抗寒性研究，莲雾、杧果主要是开展不同品种间抗寒能力定性比较的抗寒性研究[14-19]，寒冻害等级指标仅见莲雾初步研究[20]，主要

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是通过冬季1~2个低温过程总结得出，样本不足，确定的指标未进行验证。因此笔者基于历史气候、寒冻害灾情资料、地理移放试验、人工气候箱致灾试验和大尺度考察资料等多种试验和手段，对照寒冻害形态学标准，分析寒冻害调查及试验青枣、杧果、莲雾等果树的形态变化及生理生态指标变化，确定灾情样本等级，采用数理统计和对比印证方法，对3种新兴热带水果的寒冻害低温指标进行研究，以期为青枣、杧果、莲雾果树合理布局提供科学依据，以保障我国特色热带果树产业健康稳定的发展。

1 材料和方法

1.1 材料

2014—2016年春季将我国3种果树主栽品种（莲雾品种为‘黑珍珠’、杧果品种为‘台农1号’、青枣品种为‘脆蜜’）1~2 a（年）生健壮嫁接苗植入到圆形橡胶盆中，每盆植1株，置于漳州热带气象试验站、华南农业大学农业气象观测场、柳州市沙塘农业气象试验站光照条件下培养，适时浇水，15~20 d施肥1次。试验中保持植株自然状态，不作人为改变。

1.2 寒冻害形态学等级确定

根据福建、广东、广西3省区3种热带果树冻害后树体的表现症状和危害性，结合文献、专家访问等制定出寒冻害分级标准，将冻害等级划分为4个级别，分别为轻度、中度、重度、极重，并将各级别中的叶片、枝条、主干受害症状进行归纳汇总。

1.3 莲雾、杧果、青枣主产区寒冻害观测试验

2014年9月至今，在福建、广东、广西3省区7个莲雾园、7个杧果园、9个青枣园分别设置小气候观测点，记录各点逐日极端最低气温，过程低温过后调查各种植点的果树寒冻害，记录不同低温过程中3种热带果树叶片、枝条、主干等营养器官的形态变化，并将其与寒冻害形态学等级进行比较，确定各点寒冻害等级。

1.4 人工气候箱低温致灾试验

模拟自然降温过程，在气温低于20 ℃的天气开始进行试验。莲雾温度设定为5、3、2、1、0、−1、−2 ℃，进行1 d处理，其中−1 ℃又设2 d处理，−2 ℃又设2、3 d处理，共10个处理；杧果温度设定为5、3、1、−1、−2、−3、−5 ℃，进行1 d处理，其中−1 ℃又设3 d处理，−2、−3 ℃又设2、3 d处理，共12个处理；青枣温度设定为5、3、1、−1、−2、−3 ℃，进行1 d处理，其中−2 ℃又设2、3 d处理共8个处理；每个温度持续时间均为2 h，每个处理均设3个重复。每个处理均设3个重复。低温处理完毕后将试材置于户外继续培养（日最低温度≥5 ℃），7~14 d后观测形态变化，确定灾情等级。

1.5 果树苗寒冻害地理移放试验

根据福建、广东、广西3省区低温分布规律，于2014年11月至2015年1月、2015年11月至2016年1月将莲雾、青枣、杧果的盆栽苗各3~5株分别安置在福建、广东、广西共17个气象观测场或气象观测点附近。各点的地理信息见表1。对果树开展平行观测，每次冷空气来临或气温低于8 ℃时，观测记录

表1 福建、广东、广西3省区地理移放试验点信息

Table 1 The points of the geographical transplantation experiment in Fujian, Guangdong and Guangxi provinces

省区 Province	站点 Site	经度 Longitude/°E	纬度 Latitude/°N	海拔 Altitude/m	年最低温度多年均值 Multi-year average of extreme minimum temperature/℃
福建 Fujian	南靖高港 Gaogang, Nanjing	117.16	24.50	810.0	−3.0
	福鼎 Fuding	120.12	27.20	36.2	−1.9
	永泰 Yongtai	118.94	25.87	85.6	−1.2
	罗源 Luoyuan	119.55	26.50	60.5	−0.1
	平和 Pinghe	117.18	24.23	108.5	1.0
	南安 Nan'an	117.52	24.63	44.0	1.3
	漳州天宝 Tianbao, Zhangzhou	117.52	24.63	44.0	1.3
	长泰 Changtai	117.76	24.63	43.0	2.1
	龙海 Longhai	117.83	24.43	32.1	3.1
广东 Guangdong	曲江 Qujiang	113.60	24.68	60.7	−0.3
	台山 Taishan	112.78	22.25	32.7	3.8
	太平洞 Taipingdong	112.95	24.89	948.2	−2.8
	秤架 Chengjia	112.85	24.81	153.5	−0.3
	引太 Yintai	112.94	24.87	839.3	−2.6
广西 Guangxi	资源 Ziyuan	110.63	26.03	408.4	−3.8
	兴安 Xing'an	110.67	25.62	224.0	−2.2
	沙糖 Shatang	109.38	24.47	97.5	0.8

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果苗形态变化，确定其灾情等级。

1.6　寒冻害灾情样本资料收集、处理

1.6.1　历史灾情样本资料收集、处理　收集整理历史上曾导致3种热带果树寒冻害的福建、广东、广西省区历年寒冻害资料以及2014—2015、2015—2016年度冬季在福建、广东、广西3省区3种热带果树园寒冻害考察及果园气象站寒冻害调查资料。从中筛选出有明确时间、地点、果树受害症状、过程低温等有效样本莲雾89例、青枣45例、杧果60例，对照寒冻害形态学等级确定样本灾情等级X（0、0.5、1、1.5、2、2.5、3、3.5、4），其中0、1、2、3、4分别代表无、轻、中、重、极重寒冻害，0.5、1.5、2.5、3.5分别代表无~轻、轻~中、中~重、重~极重临界等级。其中考察点历史的寒冻害灾情对应的过程极端最低气温（Td），用近期县气象站或区域自动站的Td资料与各个测点的低温资料进行差值反演订正，推算出各个测点寒冻害当年冬季的Td。

1.6.2　试验灾情样本资料收集、处理　收集3种热带果树苗人工气候箱低温致灾试验、寒冻害地理移放试验、小气候致灾试验灾情样本，对照其寒冻害分级标准，分别建立灾情等级-过程低温样本集。

1.6.3　寒冻害低温等级指标确定　以2008—2015年3种果树寒冻害等级-最低气温样本采用数理统计分析方法初步确定其寒冻害低温等级指标，利用地理移放试验、人工气候箱低温致灾试验灾情及2016年果园实际灾情样本来验证，以确定3种果树寒冻害低温等级指标。

2　结果与分析

2.1　寒冻害低温等级指标的初步确定

3种果树灾情等级X与过程最低低温Td的关系分别用直线、对数、幂函数、指数函数方程进行拟合，显示一元一次、二次、三次方程的拟合效果均很好，其中莲雾各拟合方程分别为Td=7.306−2.632X、Td=6.267−1.085X−0.349X^2、Td=6.820−2.611X+0.520X^2−0.123X^3，相关系数r分别为0.952、0.953、0.954，均>0.001；杧果各拟合方程分别为Td=2.657−1.416X、Td=2.66−1.425X+0.002X^2、Td=2.732−1.969X+0.433X^2−0.077X^3，r分别为0.689 3、0.689 3、0.690 7，均>0.001；青枣各拟合方程分别为Td=6.665−2.576X、Td=6.356−2.231X−0.076X^2、Td=5.169+0.619X−1.598X^2+0.226X^3，r分别为0.840 5、0.840 8、0.847 0，均>0.001。用寒冻害等级X=0.5、1.5、2.5、3.5分别代入以上方程，3个方程均可初步得出无~轻、轻~中、中~重、重~极重等级临界低温阈值Td，将3个方程同一X得出的Td值平均，为了应用方便，取0.5 ℃整，初步确定3种果树寒冻害低温等级指标分别为莲雾：Td>5.5 ℃，无寒冻害；3.0 ℃<Td≤5.5 ℃，轻度；1.0 ℃<Td≤3.0 ℃，中度；−1.5 ℃<Td≤1.0 ℃，重度；Td≤−1.5 ℃，极重；青枣：Td>5.0 ℃，无寒冻害，正常生长；3.0 ℃<Td≤5.0 ℃，轻度；0.5 ℃<Td≤3.0 ℃，中度；−2.5 ℃<Td≤0.5 ℃，重度；Td≤−2.5 ℃，极重，不可恢复或死亡；杧果：Td>2.0 ℃，无寒冻害，正常生长；0.5 ℃<Td≤2.0 ℃，轻度；−1.0 ℃<Td≤0.5 ℃，中度；−1.0 ℃<Td≤−2.5 ℃，重度；Td≤−2.5 ℃，极重，不可恢复或死亡。

2.2　寒冻害低温指标的验证分析

2.2.1　人工气候箱致灾试验对比印证　3种果树人工气候箱致灾试验实际寒冻害等级与按照初步指标判断的等级进行对比（等级之差在0.5级以内的认为一致，下同），莲雾、杧果、青枣吻合率分别为90%、100%、100%（表2~表4）。

表2　不同低温处理设置莲雾苗寒冻害症状及对初步指标验证

Table 2　Cold and freezing injury symptoms of wax apple seeds under different low temperatures and preliminary index verification

处理方式 Treatment method	处理后症状 Symptoms post treatment	实际寒冻害等级① Actual cold and freezing injury grade①	按Td推算等级② According to the grades of Td judgment②	等级对比①-② Grade comparison ①-②
−2 ℃/2 h/1 d	冻死 Froze to death	4	4	0
−2 ℃/2 h/2 d	冻死 Froze to death	4	4	0
−2 ℃/2 h/3 d	冻死 Froze to death	4	4	0
−1 ℃/2 h/2 d	部分叶干枯，枝条受冻 Some leaves withered and branches froze	3	3	0
−1 ℃/2 h/1 d	叶干枯，枝条受冻 Leaves withered and branches froze	3	3	0
0 ℃/2 h/1 d	2株死亡，1株枝条受冻 Two froze to death, and one froze	3.5	3	0.5
1 ℃/2 h/1 d	外枝条干枯 Dry branches outside	2.5	3	−0.5
2 ℃/2 h/1 d	叶、梢受冻 Leaves and shoots froze	1.5	2	−0.5
3 ℃/2 h/1 d	大部叶片变色 Most of leaves discolored	1	2	−1.0
5 ℃/2 h/1 d	仅1株叶片褐斑 Only one plant's leaves were brown	0.5	1	−0.5

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表 3 不同低温处理设置杧果苗寒冻害症状及对初步指标的验证

Table 3 Cold and freezing injury symptoms of mango seeds under different low temperatures and preliminary index verification

处理方式 Treatment method	处理后症状 Symptoms post treatment	实际寒冻害等级① Actual cold and freezing injury grade①	按Td推算等级② According to the grades of Td judgment②	等级对比①-② Grade comparison ①-②
-5 ℃/2 h/1 d	冻死 Froze to death	4	4	0
-3 ℃/2 h/3 d	冻死 Froze to death	4	4	0
-3 ℃/2 h/2 d	冻死 Froze to death	4	4	0
-3 ℃/2 h/1 d	大部分冻死 Most of plants froze to death	3.5	4	-0.5
-2 ℃/2 h/3 d	大部分冻死 Most of plants froze to death	3.5	3	0.5
-2 ℃/2 h/2 d	大部分冻死 Most of plants froze to death	3.5	3	0.5
-2 ℃/2 h/1 d	大部分冻死 Most of plants froze to death	3.5	3	0.5
-1 ℃/2 h/3 d	叶片失水 Leaf water loss	2	2	0
-1 ℃/2 h/1 d	叶片出现斑点 Leaves had spots	2	2	0
1 ℃/2 h/1 d	叶片变色 Leaves discolored	1	1	0
3 ℃/2 h/1 d	无变化 No change	0	0	0
5 ℃/2 h/1 d	无变化 No change	0	0	0

表 4 不同低温处理设置青枣苗寒冻害症状及对初步指标的验证

Table 4 Cold and freezing injury symptoms of *Zizyphus mauritiana* seeds under different low temperatures and preliminary index verification

处理方式 Treatment method	处理后症状 Symptoms post treatment	实际寒冻害等级① Actual cold and freezing injury grade①	按Td判断等级② According to the grades of Td judgment②	等级对比①-② Grade comparison ①-②
-3.0 ℃/2 h/1 d	主枝条干枯或死亡 Boughs withered or froze to death	3.5	4	-0.5
-2.0 ℃/2 h/3 d	大部分冻死 Most of plants frozen to death	3.5	3	0.5
-2.0 ℃/2 h/2 d	大部分冻死 Most of plants froze to death	3.5	3	0.5
-2.0 ℃/2 h/1 d	外枝条、主枝末端焦枯 The outer branches and the end of boughs withered	3	3	0
-1.0 ℃/2 h/1 d	枝条、主枝末端焦枯 The branches and the end of boughs withered	3	3	0
1 ℃/2 h/1 d	叶片变色、脱水 Leaves discolored and dehydrated	2	2	0
3 ℃/2 h/1 d	叶片变色 Leaves discolored	1	1	0
5 ℃/2 h/1 d	叶片变色 Leaves discolored	1	1	0

2.2.2 地理移放试验的验证 根据2014—2015、2015—2016年冬季在福建(南靖高港、长泰、龙海、平和、南安、福鼎、永泰、罗源)、广东(曲江、台山、太平洞、引太电站、秤架二级电站)、广西(资源、兴安、沙塘、钦州)17个地点的盆栽移放试验,与按照初步指标判断的等级进行对比,莲雾、杧果、青枣验证吻合率分别为96.3%、88.2%、94.1%,结果见表5~表7。

2.2.3 2016年灾情对比印证 2016年是强低温年,我国热带果树遭受较严重寒冻害,将指标判断值与2016年莲雾11个、杧果6个、青枣10个果园的实际寒冻害灾情样本进行对比,结果见表8~表10。由表可见,用最低气温对照初步寒冻害指标查得的等级与实际寒冻害等级比较,莲雾、杧果、青枣均是除1个样本差1级外,其余样本之差均在0.5级以内,验证吻合率分别为91%、83.3%、90%。

2.3 寒冻害低温指标的最终确定

由以上验证可见,研究的等级指标通过人工气候箱致灾试验、地理移放试验和典型年结果验证,其中莲雾、青枣各种验证准确率均在90%以上,杧果分别为100%、88.2%、83.3%,说明初步确定的指标是可靠的。结合各等级形态学标准,最终确定莲雾、杧果、青枣寒冻害低温等级指标见表11~表13。

3 讨 论

果树寒冻害的发生及程度除了与果树种类、树龄有关外,主要取决于过程最低气温和低温持续时

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表5　莲雾果苗寒冻害移放试验及对初步指标的验证

Table 5 Geographical transplantation experiments of wax apple seeds and preliminary index verification

站名 Station name	2014—2015年 From 2014 to 2015					2015—2016年 From 2015 to 2016				
	实况 Observation			按Td推算等级② According to the grades of Td judgment②	等级差①-② Grade difference ①-②	实况 Observation			按Td推算等级② According to the grades of Td judgment②	等级差①-② Grade difference ①-②
	特征 Characteristic	等级① Grade①	Td/℃			特征 Characteristic	等级① Grade①	Td/℃		
南靖高港 Gaogang, Nanjing	冻死 Froze to death	4	−2.6	4	0	冻死 Froze to death	4	−1.9	4	0
长泰 Changtai	叶片变色 Leaves discolored	1	4.8	1	0	落叶>90%，出现枯枝 90% of leaves fell, dead branches appeared	3	0	3	0
龙海 Longhai	叶片轻变色 Leaves lightly discolored	0.5	5.7	0	0.5					
平和 Pinghe						100%叶片、枝条受冻 All leaves fell, branches were frosted	3	−1.4	4	0
南安 Nan'an	40%叶片变色 40% of leaves discolored	1	3.6	1	0	冻死 Froze to death	4	−2.4	4	0
福鼎 Fuding						冻死 Froze to death	4	−4.2	4	0
永泰 Yongtai	落叶60%,枝条变色80% 60% of leaves fell, 80% of branches discolored	2.5	1.8	2	0.5	100%叶片枯落，枯枝 All leaves fell, and all branches withered	4	−2.2	4	0
罗源 Luoyuan	90%落叶 90% of leaves fell	3	1.5	2	1					
曲江 Qujiang	落叶30%，1株未恢复 30% of leaves fell, one plant was not restored	2	1.7	2	0					
台山 Taishan	无冻伤 No frozing injury	0	6.6	0	0					
太平洞 Taipingdong	冻死 Froze to death	4	−2.2	4	0	冻死 Froze to death	4	−7.9	4	0
引太电站 Yintai power station	冻死 Froze to death	4	−2.9	4	0	冻死 Froze to death	4	−6.9	4	0
秤架二级电站 Pingjia power station	100%落叶 All leaves fell	3	1.0	2	0	叶干枯100% All leaves withered	3.5	−1.8	4	−0.5
资源 Ziyuan	冻死 Froze to death	4	−2.0	4	0	冻死 Froze to death	4	−2.1	4	0
兴安 Xing'an	100%落叶,枝条死亡,砧木未死 All leaves fell, and all branches died, stock did not die	3.5	0.3	3	0.5	100%落叶， All leaves fell	3.5	−0.5	3	0.5
沙塘 Shatang	出现落叶 Some leaves fell	1	3.9	1	0	100%落叶 All leaves fell	3	0.7	3	0
钦州 Qinzhou	无冻伤 No freezing injury	0	5.9	0	0					

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表6 杧果果苗寒冻害移置试验及对初步指标的验证

Table 6 Geographical transplantation experiments of mango seeds and preliminary index verification

站名 Station name	2014—2015年 From 2014 to 2015					2015—2016年 From 2015 to 2016				
	实况 Observation			按Td推算等级② According to the grades of Td judgment②	等级差①-② Grade difference ①-②	实况 Observation			按Td推算等级② According to the grades of Td judgment②	等级差①-② Grade difference ①-②
	特征 Characteristic	等级① Grade①	Td/℃			特征 Characteristic	等级① Grade①	Td/℃		
南靖高港 Gaogang, Nanjing	冻死 Froze to death	4	−2.6	4	0	100%落叶 All leaves fell	3.5	−1.9	3	0.5
长泰 Changtai	10%叶片变色 10% leaves discolored	0.5	4.8	0	0.5	叶脉变红 Veins turned red	1	0	2	−1
龙海 Longhai	正常 Normal	0	5.7	0	0					
平和 Pinghe						上部叶片变色 Upper leaves discolored	2.5	−1.4	3	−0.5
南安 Nan'an	正常 Normal	0	3.6	0	0					
福鼎 Fuding						冻死 Froze to death	4	−4.2	4	0
永泰 Yongtai	部分叶脉变红 Some veins turned red	0.5	1.8	1	−0.5	100%叶片枯黄 All leaves Withered	3	−2.2	3	0
罗源 Luoyuan	正常 Normal	0	1.5	1	−1					
资源 Ziyuan	整株叶冻死 All leaves were frozen to death	3.5	−2.0	3	0.5	冻死 Froze to death	4	−2.1	4	0
兴安 Xing'an	嫩芽、叶片局部发黑 Buds and part of leaves were black	1.5	0.3	2	0.5	叶褐色斑块 Leaves had brown spots	2	−0.5	2	0
沙塘 Shatang	出现落叶 Fallen leaves	0	3.9	0	0	50%叶片轻微变色，25%嫩叶死亡，25%叶片青枯 50% of leaves lightly discolored, 25% of young leaves died, 25% of old leaves withered	1.5	0.7	1	0.5

间[21-23]。关于香蕉、荔枝、龙眼等大宗果树的寒冻害低温等级指标[9-11]主要是基于历史灾情样本建立一元一次或一元二次方程，一个方程拟合结果得出低温冻害临界点，笔者建立了多种方程并将应用一元一次、一元二次、一元三次方程得出的临界点温度值进行平均，避免了单一方程在某一临界点的较大偏差，同时在验证时除了用地理移植试验外，还开展低温箱试验以增加验证样本。而且本研究是在福建、广东、广西3省区建立大量田间观测站，相比香蕉、荔枝、龙眼等大宗果树主要是基于早年灾情记录[9-11]，该研究实际灾情资料样本的可靠性有保障。目前未见青枣、杧果、莲雾3种果树寒冻害指标研究结果，其中莲雾仅就不同品种间抗寒能力比较研究，是将叶片在低温箱中进行恒温处理（持续1、2、3 d等），未考虑枝条、主干抗冻能力，仅可用于品种间叶片抗寒性比较[14,16-17,19,24]，与实际种植区田间冬季低温日变化不同，难以在实际生产中应用；杧果不同品种间的抗寒性是利用一个低温过程几个杧果品种（系）的寒害情况及恢复情况调查来确定其抗寒性[15]；同时考虑多种气象因子的综合寒冻害指标难以用于实时预警业务，本研究的寒冻害等级指标仅考虑最低温度这一因子，3种果树的寒冻害级别X与

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表7　青枣果苗寒冻害移置试验及对初步指标的验证

Table 7 Geographical transplantation experiments of *Zizyphus mauritiana* seeds and preliminary index verification

站名 Station name	2014—2015年 From 2014 to 2015					2015—2016年 From 2015 to 2016				
	实况 Observation			按Td推算等级② According to the grades of Td judgment②	等级差①-② Grade difference ①-②	实况 Observation			按Td推算等级② According to the grades of Td judgment ②	等级差①-② Grade difference ①-②
	特征 Characteristic	等级① Grade①	Td/℃			特征 Characteristic	等级① Grade①	Td/℃		
南靖高港 Gaogang, Nanjing	冻死 Froze to death	4	−2.6	4	0	冻死 Froze to death	4	−6.6	4	0
长泰 Changtai	幼果变色 Young fruits discolored	1	4.8	1	0	果实变黄、叶片变色萎蔫 Fruits turned yellow, leaves discolored and wilted	3	0	3	0
龙海 Longhai	幼果变色 Young fruits discolored	0.5	5.7	0	0.5					
平和 Pinghe						叶片变色 All leaves discolored	3	−1.4	3	0
南安 Nan'an	幼果100%受冻,叶片未变 All young fruits frozen, leaves did not discolor	1	3.6	1	0					
福鼎 Fuding						冻死 Froze to death	4	−4.2	4	0
永泰 Yongtai	部分幼果萎蔫,叶片卷曲变色 Part of young fruits wilted, leaves curled and discolored	2	1.8	2	0	幼果萎蔫,叶片卷曲变色 Young fruits wilted, leaves curled and discolored	3	−2.2	3	0
罗源 Luoyuan	幼果变色萎蔫,叶片卷曲变色 Young fruits wilted, leaves curled and discolored	2	1.5	2	0					
资源 Ziyuan	冻死 Froze to death	4	−2.0	3	1	冻死 Froze to death	4	−2.1	4	0
兴安 Xing'an	果实出现冻害,转色干枯 Fruits appeared with cold injuries, discolored and dried	2.5	0.3	3	−0.5	90%落叶 90% of leaves fell	3.5	−0.5	3	0.5
沙塘 Shatang	未出现明显症状 No freezing injuries or lightly	0.5	3.9	1	−0.5	幼果变色,部分叶片有斑块 Young fruits discolored, part of leaves had spots	1.5	0.7	2	0.5

表8　2016年莲雾寒冻害资料对初步指标的验证

Table 8 Validation of the cold and freezing injury data of wax apples in 2016 for preliminary indexes

地点 Site	实际寒冻害 Actual cold and freezing injury		判断等级② Judgment grade②	等级差①-② Grade difference①-②
	等级①Grade①	Td/℃		
长泰雪美 Xuemei, Changtai	3.5	−1.7	4	−0.5
长泰群力 Qunli, Changtai	3.5	−1.6	4	−0.5
漳浦长桥 Changqiao, Zhangpu	3	−0.4	3	0
漳浦绥安 Suian, Zhangpu	3	−0.3	3	0
东山前楼镇 Qianlou, Dongshan	1	2.1	1	0
东山樟溪镇 Zhangxi, Dongshan	2	2	1	1
漳州天宝 Tianbao, Zhangzhou	2.5	0.5	2	0.5
南安Nan'an	4	−2.4	4	0
福清Fuqing	3.5	−1.5	3.5	0
田阳Tianyang	1	3.6	1	0
从化Conghua	2	1.3	2	0

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表 9 2016 年杧果寒冻害资料对初步指标的验证

Table 9 Validation of the cold and freezing injury data of mangos in 2016 for preliminary indexes

地点 Site	实际寒冻害 Actual cold and freezing injury		判断等级② Judgment grade②	等级差①-② Grade difference①-②
	等级①Grade①	Td/℃		
南安 Nan'an	3	−2.4	3	0
福清 Fuqing	2	−1.5	3	0
三都澳 Sanduao	3.5	−2.5	3.5	0
武鸣 Wuming	1	2.1	0	1
右江区 Youjiang	1.5	−0.6	2	−0.5
田林县 Tianlin	1.5	0.4	2	−0.5

表 10 2016 年冬季台湾青枣寒冻害资料对初步指标的验证

Table 10 Validation of the cold and freezing injury data of *Zizyphus mauritiana* in 2016 for preliminary indexes

地点 Site	实际寒冻害 Actual cold and freezing injury		判断等级② Judgment grade②	等级差①-② Grade difference①-②
	等级①Grade①	Td/℃		
芗城浦南镇 Punan town, Xiangchen	3	0	3	0
漳浦大南坂镇 Dananban town, Zhangpu	3	−0.9	3	0
漳浦盘陀镇 Pantuo town, Zhangpu	3	−1.9	3	0
芗城天宝镇 Tianbao town, Xiangchen	2	0.5	2	0
永泰县 Yongtai	3	−2.2	3	0
南安 Nan'an	3	−2.4	3	0
云霄 Yunxiao	2	0.7	2	0
新丰 Xinfeng	3	−0.4	3	0
潮安 Chaoan	3	−0.6	3	0
北流 Beiliu	3	1.8	2	1

表 11 莲雾的寒冻害指标及树体表现症状

Table 11 Cold and freezing injury grade indexes and tree morphological symptoms of wax apples

寒冻害等级 Cold and freezing grade	过程日最低气温 Daily minimum temperature of process/℃	叶片症状 Leaf symptoms	枝条症状 Branch symptoms	主干症状 Main trunk symptoms
轻度 Light	3.0 < Td≤5.0	主脉或其基部 1/3 呈现紫色，或叶柄变褐色；嫩叶的叶尖焦枯及近叶尖叶肉呈现斑点状焦枯；脱落率≤50% The main vein of leaf or its 1/3 base appeared purple, or petiole turned brown; tip of tender leaf withered, and leaf mesophyll near tip withered like spot; expulsion rate≤50%	枝梢末端黑枯或无 The shoot tip turned black and withered, or not	无冻伤 No cold injury
中度 Moderate	1.0 < Td≤3.0	末级枝梢的叶片焦黄干枯；50% < 脱落率≤90% Leaves of the shoot tip turned yellow and withered; 50% < expulsion rate≤90%	末级枝梢受冻干枯，次级枝梢无冻伤 The shoot tip were frozen and withered, the secondary shoot had no cold injury	无冻伤 No cold injury
重度 Severe	−1.5 < Td≤1.0	树体中上部及外围叶片焦黄干枯；叶片脱落或部分干枯后挂树上 The tree in the upper part and the peripheral leaves turned yellow and withered; leaves fell, or part of leaves withered and hung on the trees	枝组受冻干枯，副主枝、主枝无冻伤 Branch groups were frozen and withered, deputy boughs and boughs were not frozen	无冻伤 No cold injury
极重 Most severe	Td≤−1.5	100%脱落或干枯后挂树上 All leaves fell, or withered and hung on the trees	枝组全冻死，副主枝、主枝全冻死或少部分保留活性 Branch groups were all frozen to death, deputy boughs and boughs were frozen to death, or a small number of them retained activity	冻伤或冻死 Cold injury or froze to death

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表12　杧果的寒冻害指标及树体表现症状

Table 12　Cold and freezing injury grade indexes and tree morphological symptoms of mangos

寒冻害等级 Cold and freezing grade	过程日最低气温 Daily minimum temperature of process/℃	叶片症状 Leaf symptom	枝条症状 Branch symptom	花序症状 Inflorescence symptom	主干症状 Main trunk symptom
轻度 Light	0.5 < Td≤2.0	叶片受害，出现水渍状斑点或斑块 Leaves were injured, and appeared water stained spots and plaques	1 a生枝条受害或无 One year old branches were injured or not	花序受害干枯<1/2 Less than 1/2 of inflorescence withered	无冻伤 No cold injury
中度 Moderate	−1.0 < Td≤0.5	大部分叶片干枯 Most leaves withered	2 a生枝条受害，逐渐干枯 Two year old branches were injured, and withered gradually	花序受害干枯1/2~2/3 1/2 to 2/3 of inflorescence withered	无冻伤 No cold injury
重度 Severe	−2.5 < Td≤−1.0	树冠受害全部干枯 Crown was injured and withered		花序全部受害干枯 All inflorescence withered	主干受害干枯 > 2/3 Greater than 2/3 of main trunk withered
极重 Most severe	Td≤−2.5	100%脱落或干枯后挂树上 All leaves fell, or withered and hung on the trees	枝组全冻死 Branch groups were all frozen to death	花序全部干枯死亡 All inflorescence withered to death	主干受害干枯死亡 Main trunk withered to death

表13　青枣的寒冻害指标及树体表现症状

Table 13　Cold and freezing injury grade indexes and tree morphological symptoms of *Zizyphus mauritiana*

寒冻害等级 Cold and freezing grade	过程日最低气温 Daily minimum temperature of process/℃	果实症状 Fruit symptom	叶片症状 Leaf symptom	枝条症状 Branch symptom	主干症状 Main trunk symptom
轻度 Light	3.0 < Td≤5.0	果皮变色、果肉不变色 Peel discolored, flesh did not discolor	嫩叶卷曲 Tender leaves curled	无冻伤 No cold injury	无冻伤 No cold injury
中度 Moderate	0.5 < Td≤3.0	果皮、果肉均变色，果实受冻率≤20% Peel and flesh discolored, the freezing rate of fruit was less than or equal to 20%	外围叶片出现卷曲 Peripheral leaves curled	顶端嫩梢受冻干枯，次级枝梢无冻伤 The top tender shoots were frozen and withered, and the secondary shoot tips were not frozen	无冻伤 No cold injury
重度 Severe	−2.5 < Td≤0.5	果皮、果肉均变色，果实受冻率 > 20% Peel and flesh discolored, the freezing rate of fruit was greater than 20%	树体中上部及外围叶片卷曲、干(青)枯、脱落，仅留底层少数叶片 Leaves in the upper part and periphery of tree curled, withered and fell, only a few layers of leaves survived	外围枝条干枯，主枝部分冻伤 Peripheral branches withered, part of the boughs were frozen	无冻伤 No cold injury
极重 Most severe	Td≤−2.5	受冻率100%，烂果 The freezing rate of fruit was 100%, all fruit rotted	100%脱落或干枯后挂树上 All leaves fell, or withered and hung on the trees	枝条、主枝均褐变、干枯 Branches and boughs turned brown and withered	冻伤或冻死 Cold injury or froze to death

过程最低气温Td相关密切，随着Td的降低，寒冻害趋向严重；Td与寒冻害等级X用线性、一元二次、一元三次方程拟合效果均很好，利用回归分析初步确定3种果树轻、中、重、极重的寒冻害等级指标。

以往研究很少开展指标验证，仅有香蕉、荔枝、龙眼主要基于果树苗移放的寒冻害试验、历史典型年寒冻害灾情资料进行验证[9-11]。笔者根据初步确定的指标，利用在福建、广东、广西3省区2 a生果树苗移放的寒冻害试验、人工致灾低温箱试验、2016年寒冻害实时灾情资料验证，分析各样本实际寒冻害等级与样本所处低温，按初步寒冻害指标所对应等级差异，统计各种验证吻合率。开展多种试验资料、实时灾情资料验证，其中人工致灾低温箱试验仅莲雾10个处理除了2016年3 ℃正好处于临界温度差1个等级外，其余均吻合，吻合率达90%，杧果、青枣吻合率均100%；果树苗移放的寒冻害试验，莲雾共27个样本，除了罗源2014年等级相差1级外，其他均吻合，吻合率为96.3%，杧果共17个样本，除了罗源2014、2015年、长泰2015年等级相差1级外，其他均吻合，吻合率为88.2%，青枣共17个样本，除了资源2014等级相差1级外，其他均吻合，吻合率为94.1%；由2016典型低温年寒冻害实际灾情验证结

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果可见，莲雾11个样本除1个样本差1级外，其余10个样本均一致，占91%，杧果6个样本除1个样本差1级外，其余5个样本均一致，占83.3%，青枣10个样本除1个样本差1级外，其余9个样本均一致，占90%。结果表明，研究的等级指标通过人工气候箱致灾试验、地理移放试验和典型年结果验证，其中莲雾、青枣各种验证准确率均在90%以上，杧果分别为100%、88.2%、83.3%，验证吻合率比香蕉、荔枝、龙眼（各种吻合率大多介于67%~80%）[9-11]高得多，可见初步确定的指标是可靠的。所确定的莲雾、青枣、杧果树的轻、中、重、严重寒冻害各级指标是3种特色热带果树寒冻害监测预警、生产区划及产业带建设的重要依据。

4 结 论

确定了对应形态学指标的3种热带特色果树寒冻害低温等级指标，研究的等级指标通过人工气候箱致灾试验、地理移放试验和典型年结果验证，其中莲雾、青枣各种验证准确率均在90%以上，杧果分别为100%、88.2%、83.3%，可以在生产实际中应用。

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